

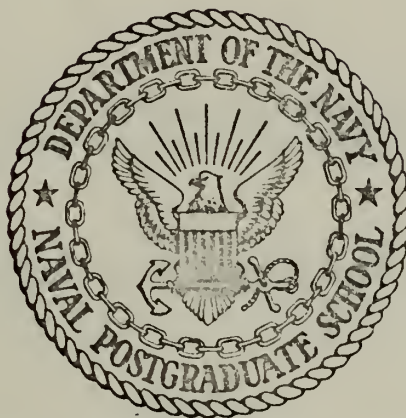
SIMULATION OF LOW SPEED
FORWARD SHIP MOTION IN THE WIND

Behlül Özdemir

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THESIS

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FORWARD SHIP MOTION IN THE WIND

by

Behlül Özdemir

Thesis Advisor:

G. J. Thaler

December 1972

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Simulation of Low Speed Forward Ship Motion in the Wind

by

Behlül Özdemir
Lieutenant(jg), Turkish Navy
B.S., Naval Postgraduate School, 1972

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ABSTRACT

The objective of this study was to examine the relationship between forward ship motion and the effects of aerodynamic and hydrodynamic disturbances on motions in the horizontal plane. It includes course control and stability analysis for the unsteered and steered cases (manual and automatic) using several sets of operating conditions.

Hydrodynamic and aerodynamic effects are considered to be functions of hull motion, rudder (steered cases), propeller and wind effects ratio. A dimensionless mathematical model has been developed and solved with respect to ship axes.

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PHYSICAL QUANTITIES

a_i	Coefficients of perturbation equation in yaw
b_i	Coefficients of perturbation equation in sway
c_i	Coefficients of perturbation equation in surge
\vec{F}	Force on the body
J_z	Moment of inertia referred to z-axis
l	Ship length
M	Moment about origin
m	Mass of ship
N	Hydrodynamic and aerodynamic yaw moment
N_a	Aerodynamic yaw moment
$N_{\dot{r}}$	Derivative of hydrodynamic yaw moment with respect to yaw acceleration
N_v	Derivative of hydrodynamic yaw moment with respect to sideslip velocity
N_s	Derivative of hydrodynamic yaw moment with respect to rudder angle
R	Vector distance of a point from the origin, and the components along the X, Y, and Z axis $\vec{R} = \vec{i}x + \vec{j}y + \vec{k}z$
r	Yaw rate
U	Velocity of the origin $\vec{U} = \vec{i}u + \vec{j}v + \vec{k}w$
u_e	Component of equilibrium ship speed in x-axis direction
u_a	Component of ship velocity relative to air in x-axis direction
U_a	Ship velocity relative to air
U_A	Wind velocity relative to earth

v	Component of ship speed in y-axis direction
v_a	Component of ship velocity relative to air in y-axis direction
v_e	Component of equilibrium ship speed in y-axis direction
X	Hydrodynamic and aerodynamic force component in x-axis direction
X_a	Aerodynamic force component in x-axis direction
X_p	Hydrodynamic force component in x-axis direction due to propeller
X_u	Derivative of hydrodynamic force component in x-axis direction, with respect to surge acceleration
X_{vr}	Second derivative of hydrodynamic force component in x-axis direction, with respect to sideslip velocity and yaw angular velocity
X_o	Drag coefficient
X_{ss}	Second derivative of hydrodynamic force component in x-axis direction, with respect to rudder angle
Y	Hydrodynamic and aerodynamic force component in y-axis direction
Y_a	Aerodynamic force component in y-axis direction
Y_r	Derivative of hydrodynamic force component in y-axis, with respect to yaw rate
Y_v	Derivative of hydrodynamic force component in y-axis direction, with respect to sideslip acceleration
Y_v	Derivative of hydrodynamic force component in y-axis direction, with respect to rudder angle

δ	Rudder angle
δ_e	Equilibrium rudder angle
ρ	Density of water
ρ_a	Density of air
ψ	Heading angle of ship
ψ_a	Direction of wind velocity relative to ship
ψ_A	Direction of wind velocity relative to earth
Ω	Angular velocity of the body about the origin
$\vec{\Omega} = \vec{i}p + \vec{j}q + \vec{k}r$	

DIMENSIONLESS FORMS

<u>Quantities</u>	<u>Typical Symbol</u>	<u>Typical Dimensionless Form</u>
Length	X_r	$X'_r = X_r/\ell$
Force	Y	$Y' = Y/\frac{e}{2}\ell^2U^2$
Moment	N	$N' = N/\frac{e}{2}\ell^3U^3$
Mass	m	$m' = m/\frac{e}{2}\ell^3$
Angular velocity	r	$r' = r\ell/U$
Static force rate	Y_v	$Y'_v = Y_v/\frac{e}{2}\ell^2U$
Static moment rate	N_v	$N'_v = N_v/\frac{e}{2}\ell^3U$
Rudder force rate	Y_s	$Y'_s = Y_s/\frac{e}{2}\ell^2U^2$
Damping force rate	Y_r	$Y'_r = Y_r/\frac{e}{2}\ell^3U$
Damping moment rate	N_r	$N'_r = N_r/\frac{e}{2}\ell^4U$
Inertial coefficient	$Y_{\dot{v}}$	$Y'_{\dot{v}} = Y_{\dot{v}}/\frac{e}{2}\ell^3$
Moment of inertia	I_z	$I'_z = I_z/\frac{e}{2}\ell^5$
Acceleration	\dot{u}	$\dot{u}' = \dot{u}\ell/U^2$
Velocity	u	$u' = u/U$
Angular acceleration	\dot{r}	$\dot{r}' = \dot{r}\ell^2/U^2$
Density of air	e_a	$e'_a = e_a/e$
Inertial coefficient	$N_{\dot{r}}$	$N'_{\dot{r}} = N_{\dot{r}}/\frac{e}{2}\ell^5$

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I. INTRODUCTION

In the last twenty years many mathematical derivations have been performed in the area of motion of vehicles in a fluid medium. Some of these mathematical models have been derived using the six degree of freedom equations of motion.

In this study of six degree freedom equations are reduced to three degrees of freedom with several assumptions. Low ship speed is assumed and coupling effects of roll, pitch and heave motion on to the horizontal plane motion are assumed negligible. It is also assumed that atmospheric motion is uniform.

Aspects of the problem are simultaneous consideration of hydrodynamic and aerodynamic effects as well as nonlinearity in the external disturbances (especially in aerodynamic terms). Equilibrium conditions and perturbation equations are derived from the mathematical model. Nonlinear parts of the mathematical model are linearized with respect to equilibrium conditions.

The effects of wind disturbances on ship motions are studied. A digital computer (IBM model 360/67) was used to solve the transient response in yaw and sway for three different wind directions (head, beam, stern) and constant wind velocities with constant ship speed. Also the eigen value theorem was used to study ship stability. All these computations were made for the unsteered (zero degree rudder deflection) and steered case (with manual as well as automatic control).

When wind velocities are several times the ship speed, even moderate winds create difficulty in controlling the ship course and stability (at low ship speeds). These effects may or may not be controllable, since the hull hydrodynamic reactions are reduced and ship motion is greatly effected by wind force, propeller thrust and coupled rudder force. This situation can cause unusually large hull drift angles extending to between plus or minus 180 degrees. The usual hull hydrodynamic force representation is not applicable beyond 15 to 20 degrees.

II. THE MATHEMATICAL MODEL

A. COORDINATE SYSTEMS AND SHIP MOTION

The coordinate system is defined with respect to the ship itself. It's coordinate origin is chosen to be the center of gravity of the ship as shown in Figure 1.

Positive X axis (lengitudinal axis) is directed to the forward direction along the center line of the ship.

Positive Y axis (transverse axis) is directed to star-board, perpendicular to the plane of symmetry.

Positive Z axis is directed downward, and lies in the vertical symmetry plane, perpendicular to the X-Y plane.

Yaw is a retatienal motion of the ship about the Z axis. (Assume that the ship is moving in the positive X direction and that a moment is applied about the Z axis tending to rotate or turn the ship in clockwise direction as indicated in Figure 2 which shows the positive yaw).

1. Equations of Motion (on the horizontal plane)

The dynamic response in six degrees freedom for the motion of a rigid body [7] is given by equation (1).

$$\begin{aligned} X &= M[\dot{U}-RV+QW-X_6(R^2+Q^2)+Y_6(PQ-\dot{R})+Z_6(PR+\dot{Q})] \\ Y &= M[\dot{V}-PW+RU+X_6(\dot{R}+PW)-Y_6(P^2+R^2)+Z_6(RQ-\dot{P})] \\ Z &= M[\dot{W}-QU+PV+X_6(PR-\dot{Q})+Y_6(\dot{P}+QR)-Z_6(Q^2+P^2)] \\ L &= \dot{P}I_X+(I_Z-I_Y)QR+M[Y_6(\dot{W}-QV+PV)-Z_6(\dot{V}-PW+RU)] \\ M &= \dot{Q}I_Y+(I_X-I_Z)PR+M[Z_6(\dot{U}-RV-QW)-X_6(\dot{W}-QU+PV)] \\ N &= \dot{R}I_Z+(I_Y-I_X)PQ+M[X_6(\dot{V}-PW+RU)-Y_6(\dot{U}-RV+QW)] \end{aligned} \quad (1)$$

These equations represent the reaction of the rigid body. They do not include external forces such as rudder force, wind force, aerodynamic and hydrodynamic force of water etc. Applied external hydrodynamic and aerodynamic forces are considered to be functions of hull motion, rudder angle, propeller and wind.

Assuming that roll, pitch, and heave motions may be neglected on the horizontal plane and that x_6, y_6, z_6 are zero for the center of gravity at the origin of the system and noting that on the horizontal plane $\vec{U} = \vec{i}u + \vec{j}v$ (linear velocity), then equation (1) becomes

$$\begin{aligned}
 X &= M[\dot{U} - RV] & (\text{Surge}) \\
 Y &= M[\dot{V} + RU] & (\text{Sway}) \\
 Z &= 0 \\
 L &= 0 \\
 M &= 0 \\
 N &= \dot{R}I_z & (\text{Yaw}) & (2)
 \end{aligned}$$

These equations are nonlinear. Analytic solution and computer simulation are very difficult. But all nonlinear terms might be linearized by using the Taylor series expansion.

Briefly, small perturbations are considered for:

$$\begin{aligned}
 X &= m(\dot{u} - rv) \\
 Y &= m(\dot{v} + ru) \\
 N &= \dot{r}I_z & (3)
 \end{aligned}$$

The external force and moments to be included are: [4]

$$X = X(\text{hull}) + X(\text{rudder and prop.}) + X(\text{wind})$$

$$Y = Y(\text{hull}) + Y(\text{rudder and prop.}) + Y(\text{wind})$$

$$N = N(\text{hull}) + N(\text{rudder and prop.}) + N(\text{wind}) \quad (4)$$

So N , X , Y represent total hydrodynamic and aerodynamic forces and moments which are generated by the ship motion, rudder, propeller and wind. The following assumptions permit elimination of relatively unimportant terms in the hydrodynamic and aerodynamic expressions: [1]

1. Ship asymmetry with respect to the centerline plane is minor (this permits elimination of odd ordered terms for the X force expansion and even ordered terms from the Y and N expansion).

2. All terms higher than third order are unimportant.

3. Rudder force and moment derivatives of higher than first order, and effects of rudder angular rate are negligible.

4. The longitudinal component of ship speed is much greater than the lateral component ($u \gg v$).

5. Based on experimental and analytical results, nonlinear hydrodynamic terms in the yaw and sway equation for the stability analysis are considered minor, except for certain nonlinear hydrodynamic terms in the surge equations such as x_{vr}' .

6. Atmospheric motion is uniform.

Thus equation (4) may be written as: [1]

$$X = C_1 \dot{u} + C_2 u^2 + C_3 vr + C_4 u^2 \delta^2 + x_1 v_a U_a + x_p$$

$$\begin{aligned}
Y &= B_1 \dot{v} + B_2 uv + B_3 ur + b_y U^2 \delta + Y_1 v_a U_a \\
N &= A_1 \dot{r} + A_2 uv + A_3 ur + A_4 v^2 \delta + N_1 u_a v_a + N_2 v_a U_a
\end{aligned} \tag{5}$$

All hydrodynamic and aerodynamic constants are defined in the appendix.

The hydrodynamic effects, forces are defined as a function of the acceleration and velocities of the hull.

The rudder deflection will also produce an additional resistance, an axial force proportional to S^2 . This force is expected to be small. The lateral force and moment are proportional to S . [5]

Forces and moments due to wind acting on the above water portions of the hull act on the ship in the horizontal plane. It is necessary to determine the relative wind speed and direction with respect to the ship in its own reference frame.

Magnitude and direction of wind is shown on Figure 1. The relative wind speed components along the ship axes are

$$\begin{aligned}
u_a &= u + U_a \cos(\psi_a + \psi) && \text{in X direction} \\
v_a &= v - U_a \sin(\psi_a + \psi) && \text{in Y direction}
\end{aligned}$$

Then

$$U_a = (u_a^2 + v_a^2)^{\frac{1}{2}}, \quad \psi_a = \tan^{-1} \frac{v_a}{u_a} \tag{6}$$

U_a and ψ_a are wind velocity and direction along the earth axis.

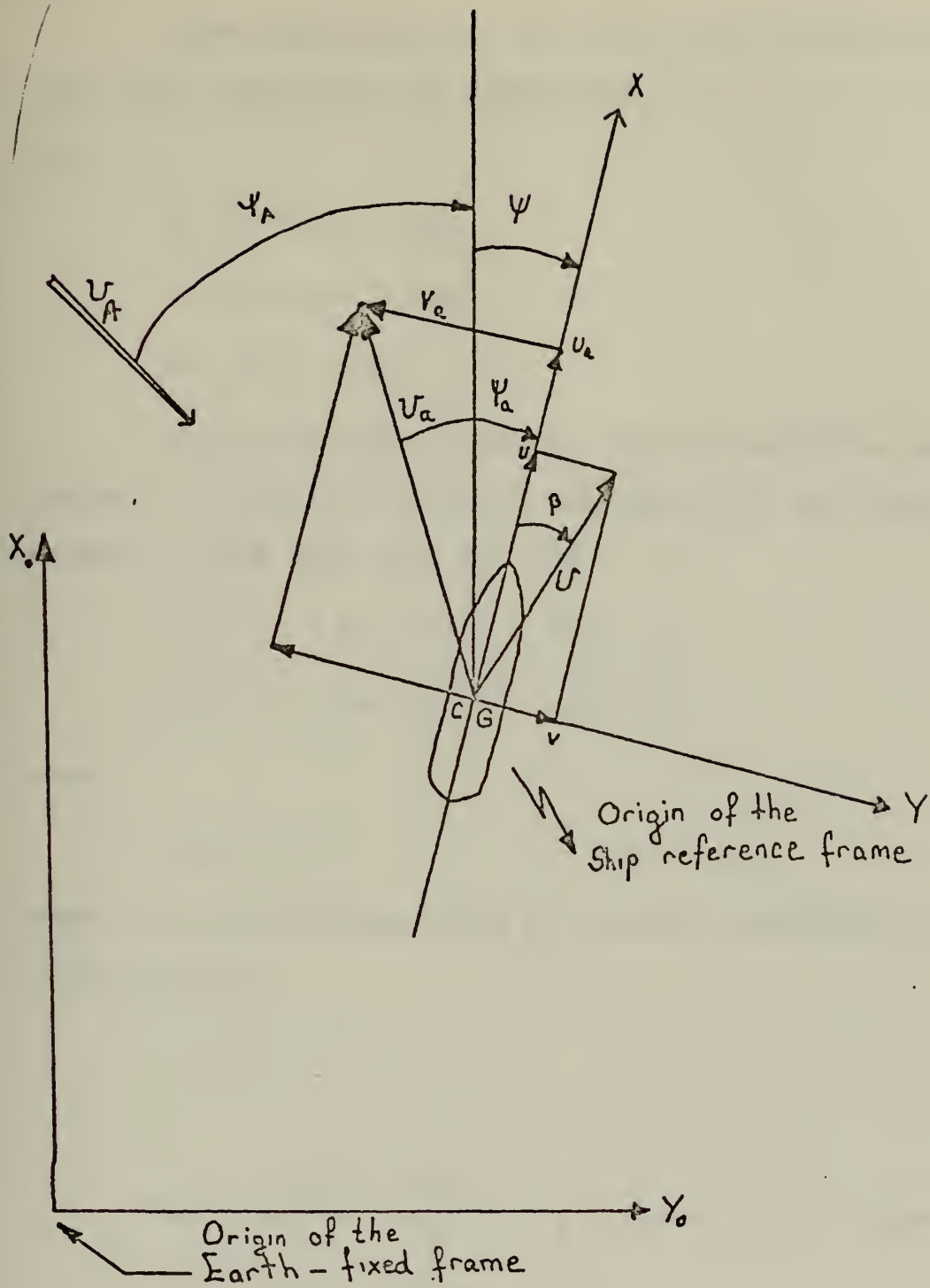


Figure 1. Relation of Wind Velocity and Direction to the Ship Axes.

From equations (3), (4), and (5), accelerations in yaw, sway, and surge are determined:

So

$$\dot{X} = \dot{u}(m - x\dot{u}) - mrv$$

$$\dot{Y} = \dot{v}(m - y\dot{v}) + mru$$

$$\dot{N} = \dot{r}(I_z - N\dot{r}) \quad (7)$$

The relationship between velocities of the ship with respect to the earth axis and velocities of the ship with respect to the body axis is: [3]

$$\dot{Y}_O(t) = u \sin(\psi) + v \cos(\psi)$$

$$\dot{X}_O(t) = u \cos(\psi) - v \sin(\psi)$$

also

$$\dot{\psi}(t) = r \quad (8)$$

Where ψ is the heading angle of the ship relative to the original path.

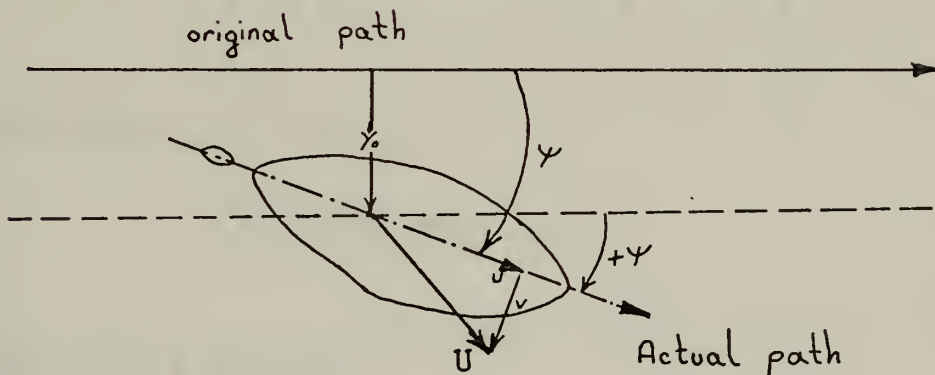


Figure 2. Positive Direction of Yaw.

$$Y_o = \int (u \cdot \sin(\psi) + v \cdot \cos(\psi)) dt + Y_o(0)$$

$$X_o = \int (u \cdot \cos(\psi) - v \sin(\psi)) dt + X_o(0) \quad (9)$$

when ψ is small:

$$\sin(\psi) \approx \psi, \quad \cos(\psi) \approx 1 \quad U \approx U_e \text{ (equilibrium case)} \quad (10)$$

So

$$\dot{Y}_o(t) = U_e \cdot \psi + v$$

$$X_o(t) = U_e - v \cdot \psi \quad (11)$$

Combining equation (5) and (7) and putting in nondimensional form. [2]

$$\begin{aligned} \frac{\rho}{2} \ell^3 (m' - x \dot{u}') \dot{W} &= \frac{\rho}{2} \ell^2 [(x'_o + x_{ss}') \delta^2 u^2 + \ell (x'_{vr} + m') v r + \rho'_a x'_a U_a^2 + x'_p U_p^2] \\ \frac{\rho}{2} \ell^3 (m' - y \dot{v}') \dot{V} &= \frac{\rho}{2} \ell^2 [y'_v u v + \ell (y'_r - m') u r + y' \delta u^2 + e'_a y'_a U_a^2] \\ \frac{\rho}{2} \ell^5 (I'_z - N'_r) \dot{r} &= \frac{\rho}{2} \ell^3 [N'_v u v + \ell N'_r u r + N' \delta u^2 + e'_a N'_a U_a^2] \end{aligned} \quad (12)$$

where

$$\begin{aligned} \frac{\rho}{2} a^3 U_a^2 N'_a &= N_a = \frac{\rho}{2} \ell^3 U^2 N'_a \\ N'_a &= \rho'_a U_a'^2 \left(\frac{N_{a1}'}{2} \sin(2\psi_a) + \frac{N_{a2}'}{2} \sin(\psi_a) \right) \end{aligned}$$

$$\begin{aligned} \frac{\rho}{2} a^2 U_a^2 y'_a &= y_a = \frac{\rho}{2} \ell^2 U^2 y'_a \\ y'_a &= \rho'_a U_a'^2 y'_{a1} \sin(\psi_a) \end{aligned}$$

$$\begin{aligned} \frac{\rho}{2} a^2 U_a^2 x'_a &= x_a = \frac{\rho}{2} \ell^2 U^2 x'_a \\ x'_a &= \rho'_a U_a'^2 x'_{a1} \cos(\psi_a) \end{aligned} \quad (13)$$

$$\rho'_a = \rho_a / \rho \quad , \quad u \approx U \quad \text{since } u \gg v$$

Expanding in Taylor's series around the equilibrium conditions:

$$\begin{aligned} u &= u_e & v &= v_e & \delta &= \delta_e \\ r &= \dot{x} = \ddot{x} = \dot{u} = \dot{v} = & & & & = 0 \end{aligned} \quad (14)$$

Substitute equation (14) into equation (12)

$$\begin{aligned} N'_v u_e v_e + N'_\delta \delta_e u_e^2 + N'_a u_e^2 &= 0 \\ Y'_v u_e v_e + Y'_\delta \delta_e u_e^2 + Y'_a u_e^2 &= 0 \\ x'_o u_e^2 + x'_{\delta\delta} \delta_e^2 u_e^2 + x'_a u_e^2 + x'_p u_e^2 &= 0 \end{aligned} \quad (15)$$

Sideslip velocity and rudder angle in the equilibrium condition can be expressed as: [1]

$$\begin{aligned} v_e' &= \frac{Y'_a N'_\delta - N'_a Y'_\delta}{N'_v Y'_\delta - Y'_v N'_\delta} \\ \delta_e &= \frac{N'_a Y'_v - Y'_a N'_v}{N'_v Y'_\delta - Y'_v N'_\delta} \end{aligned} \quad (16)$$

Perturbation terms (small deviation from the initial straight course) may be denoted by bars. So actual motion is

$$\begin{aligned} u_e &= u_e + \bar{u} & v &= v_e + \bar{v} & s &= s_e + \bar{s} & \psi &= \bar{\psi} \\ \dot{\psi} &= \dot{\bar{\psi}} & \dot{u} &= \dot{\bar{u}} & \dot{v} &= \dot{\bar{v}} \end{aligned} \quad (17)$$

Perturbations in aerodynamic quantities due to $\bar{\psi}$, \bar{v} and \bar{u} are:

$$\begin{aligned}
\bar{N}'_a &= \frac{\partial N'_a}{\partial \psi} \bar{\psi} + \frac{\partial N'_a}{\partial v'} \bar{v}' + \frac{\partial N'_a}{\partial u'} \bar{u}' \\
\bar{Y}'_a &= \frac{\partial Y'_a}{\partial \psi} \bar{\psi} + \frac{\partial Y'_a}{\partial v'} \bar{v}' + \frac{\partial Y'_a}{\partial u'} \bar{u}' \\
\bar{X}'_a &= \frac{\partial X'_a}{\partial \psi} \bar{\psi} + \frac{\partial X'_a}{\partial v'} \bar{v}' + \frac{\partial X'_a}{\partial u'} \bar{u}'
\end{aligned} \tag{18}$$

Where

$$\begin{aligned}
\frac{\partial N'_a}{\partial \psi} &= \rho'_a [(N'_{a1} \cos 2\psi_a + N'_{a2} \cos \psi_a) (U'^2_a - u'_a) \\
&\quad - 2U'_a \sin \psi_a (\frac{N'_{a1}}{2} \sin 2\psi_a + N'_{a2} \sin \psi_a)] \\
\frac{\partial N'_a}{\partial v'} &= -\rho'_a U'_a [(N'_{a1} \cos 2\psi_a + N'_{a2} \cos \psi_a) + 2(\frac{N'_{a1}}{2} \sin 2\psi_a \\
&\quad + N'_{a2} \sin \psi_a) \sin \psi_a] \\
\frac{\partial N'_a}{\partial u'} &= \rho'_a U'_a [(N'_{a1} \cos 2\psi_a + N'_{a2} \cos \psi_a) (-\sin \psi_a) \\
&\quad + 2(\frac{N'_{a1}}{2} \sin 2\psi_a + N'_{a2} \sin \psi_a) \cos \psi_a] \\
\frac{\partial Y'_a}{\partial x} &= \rho'_a Y'_{a1} [\cos \psi_a (U'^2_a - u'_a) - 2U'_a \sin^2 \psi_a] \\
\frac{\partial Y'_a}{\partial v'} &= -\rho'_a U'_a Y'_{a1} (1 + \sin^2 \psi_a) \\
\frac{\partial Y'_a}{\partial u'} &= \rho'_a U'_a Y'_{a1} \cos \psi_a \sin \psi_a
\end{aligned}$$

$$\frac{\partial X'_a}{\partial x} = -\rho'_a X'_{a1} \sin \psi_a (U'^2_a + u'_a)$$

$$\frac{\partial X'_a}{\partial v'} = -\rho'_a X'_{a1} U'_a \cos \psi_a \sin \psi_a$$

$$\frac{\partial X'_a}{\partial u'} = \rho'_a X'_{a1} U'_a (1 + \cos^2 \psi_a) \quad (19)$$

The coefficients in equation (19) were taken from reference [2]. Aerodynamic coefficients are shown in Figure 3.

Substitute equation (17) and (18) into equation (12) and obtain the perturbation equation in the following form:

$$(m' - x'_{\dot{u}}) \ddot{u}' = (\delta_{vr}' + m') v_e' \bar{r}' + \frac{2x'_a}{2x} \bar{\psi} + \frac{2x'_a}{2v'} \bar{v}' + (2x'_o + 2x'_{\delta\delta} \delta_e^2 + \frac{2x'_a}{2u'})$$

$$\bar{u}' + 2x'_{\delta\delta} \delta_e \bar{\delta}$$

$$(m' - y'_{\dot{v}}) \ddot{v}' = (y'_v - m') \bar{r}' + \frac{2y'_a}{2x} + (y'_v + \frac{2y'_a}{2v'}) \bar{v}' + (y'_v v'_e + 2y'_{\delta} \delta_e + \frac{2y'_a}{2u'})$$

$$\bar{u}' + y'_{\delta} \bar{\delta}$$

$$(I'_z - N'_{\dot{r}}) \ddot{r}' = N'_r \bar{r}' + \frac{2N'_a}{2\psi} \bar{\psi} + (N'_v + \frac{2N'_a}{2v'}) \bar{v}' + (N'_v v'_e + 2N'_{\delta} \delta_e + \frac{2N'_a}{2u'})$$

$$\bar{u}' + N'_{\delta} \bar{\delta}$$

(20)

The mathematical model which is shown in the above equations is developed only for the forward ship motion. The stern ship motion equations are written by putting negative signs in front of some of the coefficients.

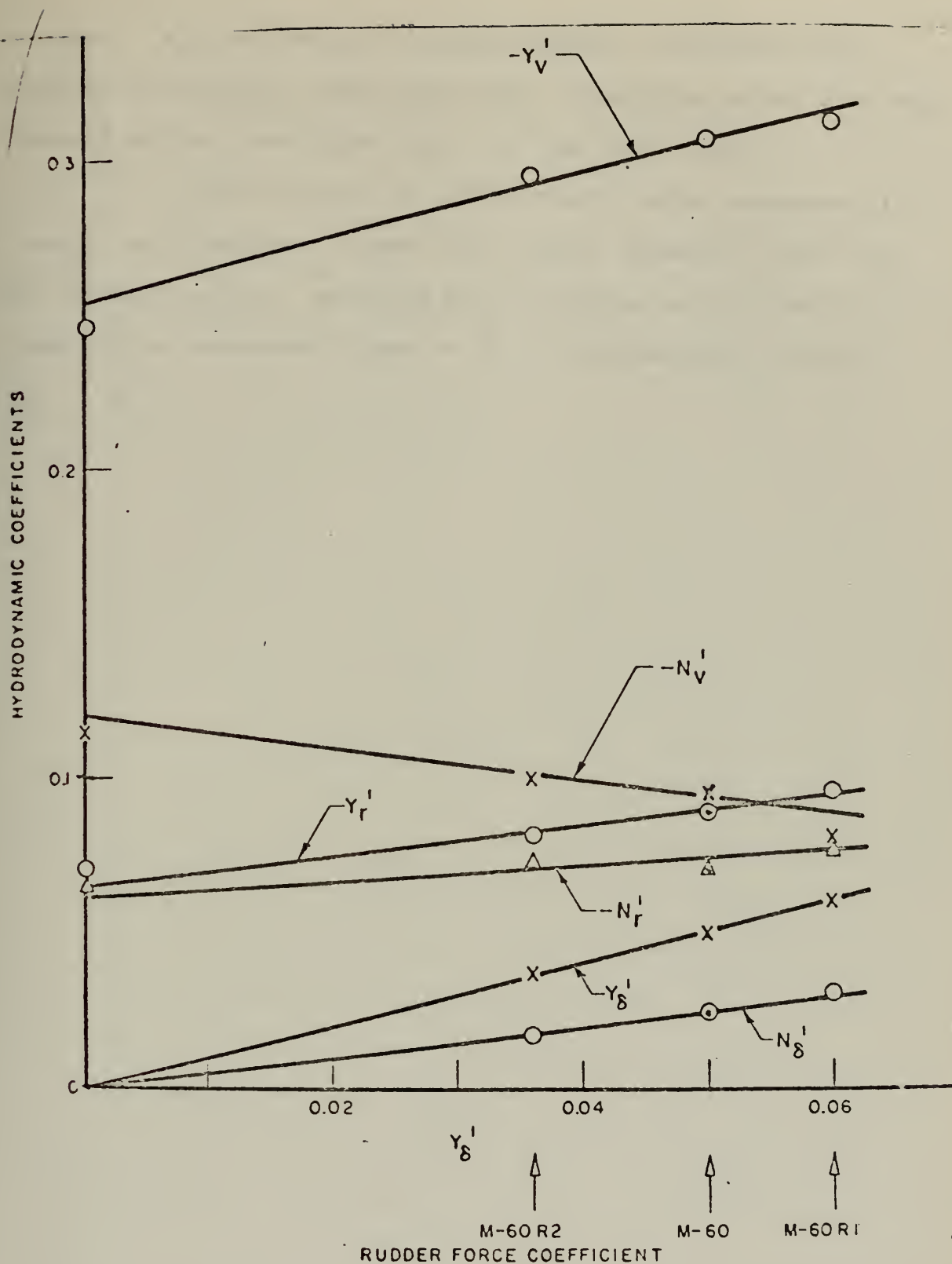


Figure 3. Hydrodynamic Coefficients Vs Rudder Force Coefficient.

Example: N_v (derivative of hydrodynamic yaw moment with respect to sideslip velocity) takes a negative value for the forward motion, positive value for the stern motion.

Y_r (derivative of hydrodynamic force component in Y-axis, with respect to yaw rate) takes negative value for the forward motion, positive for the stern motion but is not a sensitive parameter since m' is the predominant term in $(Y_r' - m')$.

III. CONTROL STUDIES

The linearized equation of motion was derived and found in equation (20). In this part two different problems were simulated. One of them was manually steered ship motion in wind disturbance. The other was automatically steered ship motion under the same effect. So computer program (II) and (III) were developed for these purposes respectively. The computer model is shown in Figure 4, for these programs. Program (II) and (III) are similar to each other. There is only one difference in section 4 of both programs. Program (II) was integrated using the second order equation, however program (III) was integrated with the third order equation. This difference was caused by the feedback loop (page 38). Also the Laplace Transform Technique could have been used to obtain the system description for simplicity and system characteristic equation for the parameter plane program. The characteristic equation was calculated in the computer program. Also three more additional and different mathematical sections were calculated in the same program. One of these sections included the parameter calculation from equation (6) through equation (20). Secondly the transfer functions of yaw and sway were calculated from the three degree of freedom equation. The last section was the polynomial calculation for the eigen values.

The last program, (parameter plane (IV)), was used to get optimal values for yaw gain constant and yaw rate gain constant using the constant zeta (function omega) and constant

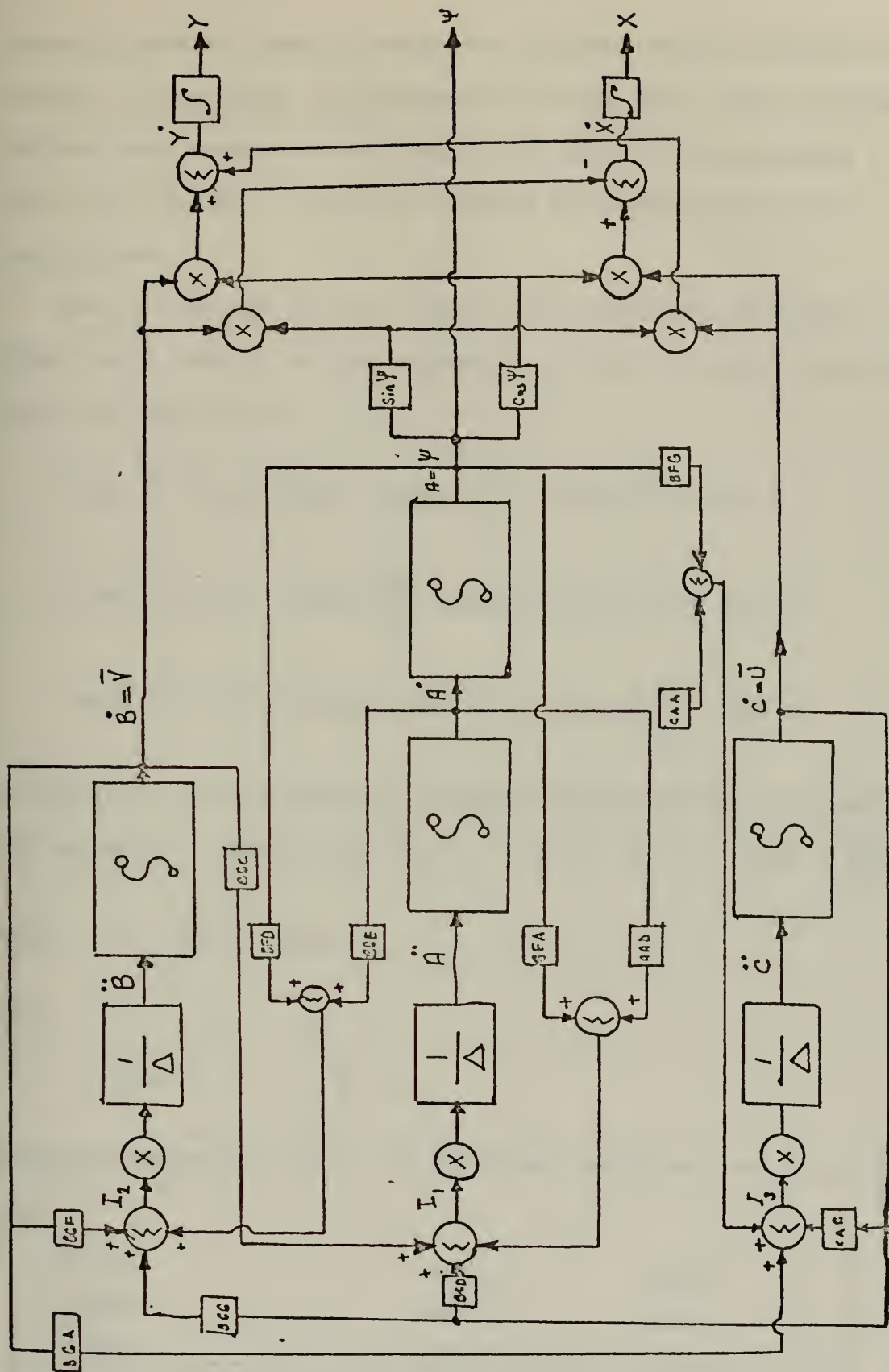


Figure 4. Computer Model for Program II and III.

omega (function zeta) curves for automatically steered ship motion. According to reference [1] and [6], these optimal values were chosen from Figures 40 through 44 assuming zeta = 6, omega = 11.5 for varying wind direction and velocities.

The transform of the linearized equations of motion (20) from the T domain to the S domain, for all initial conditions equal to zero are:

$$\begin{aligned}
 (ABC.S^2 - AAD.S - BFA)\bar{\psi} - (BGD.S)\frac{\bar{U}}{\delta} - (BGC.S)\frac{\bar{V}}{\delta} &= AAE.\bar{\delta} \\
 (-BGE.S - BFD)\bar{\psi} - (BGG.S)\frac{\bar{U}}{\delta} + (ABD.S^2 - BGF.S)\frac{\bar{V}}{\delta} &= AAC.\bar{\delta} \\
 (-CAA.S - BFG)\bar{\psi} + (ABE.S^2 - CAB.S)\frac{U}{\delta} - (BGA.S)\frac{\bar{V}}{\delta} &= CAC.\bar{\delta}
 \end{aligned} \tag{21}$$

In equation (21) different letters are used for simplicity.

For example: $ABC = I'_z - N'_r$, $AAD = N'_r$, $BFA = \frac{\partial Na'}{\partial \psi}$,

$ABE = m' - x'_u$, etc.

let

$$\frac{\bar{U}}{S} = C, \quad \frac{\bar{V}}{S} = B$$

Applying Cramer's rule, the transfer function for $\frac{\psi}{S}$ and $\frac{B}{S}$ are:

$$\frac{\bar{\psi}}{S} = \frac{
 \begin{vmatrix}
 AAE & -BGD.S & AAE \\
 AAC & -BGG.S & AAC \\
 CAC & ABE.S^2 - CAB.S & CAC
 \end{vmatrix}
 }{
 \begin{vmatrix}
 (ABC.S^2 - AAD.S - BFA) & -BGD.S & -BGC.S \\
 (-BGE.S - BFD) & -BGG.S & ABD.S^2 - BGF.S \\
 (-CAA.S - BFG) & ABE.S^2 - CAB.S & -BGA.S
 \end{vmatrix}
 } \tag{22}$$

The open loop transfer function is:

$$\frac{\psi}{\delta} = \frac{VVA.S^2 + VVC.S + VVF}{SSA.S^4 + SSB.S^3 + SSE.S^2 + SBS.S + SES} \quad (22)$$

Where

$$VVA = -ABC.ABD.ABE \quad \text{etc.}$$

All terms were calculated using program 1.

In this case, the results are a second order numerator and fourth order denominator.

Transfer function $\frac{B(s)}{\bar{\delta}(s)}$, was also obtained using Cramer's rule.

$$\frac{B}{\bar{\delta}} = \frac{\begin{vmatrix} ABC.S^2 - AAD.S - BFA & -BGD.S & AAE \\ -BGE.S - BFD & -BGG.S & AAC \\ -CAA.S - BFG & ABE.S^2 - CAB.S & CAC \end{vmatrix}}{\begin{vmatrix} ABC.S^2 - AAD.S - BFA & -BGD.S & -BGC.S \\ -BGE.S - BFD & -BGG.S & ABD.S^2 - BGF.S \\ -CAA.S - BFG & ABE.S^2 - CAB.S & -BGA.S \end{vmatrix}} \quad (23)$$

The transfer function between B and $\bar{\delta}$ is:

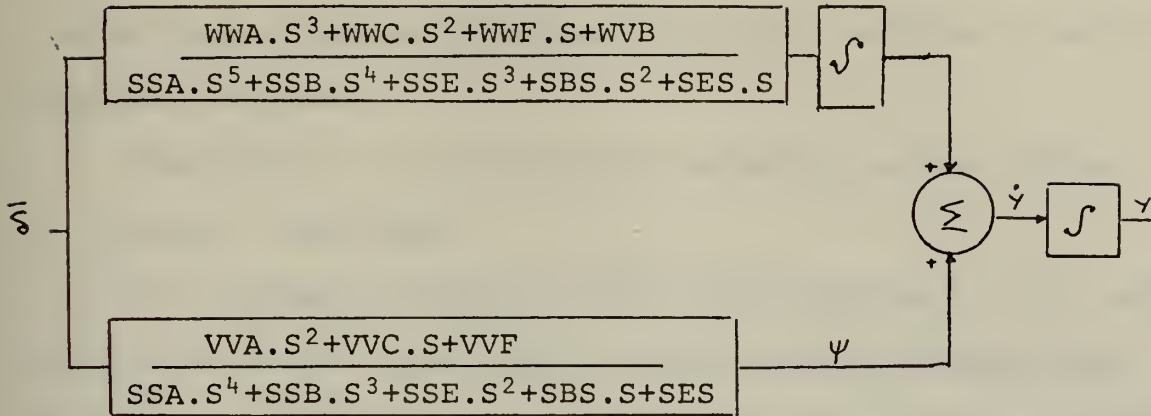
$$\frac{B}{\bar{\delta}} = \frac{WWA.S^3 + WWC.S^2 + WWF.S + WVB}{SSA.S^5 + SSB.S^4 + SSE.S^3 + SBS.S^2 + SES.S} \quad (24)$$

where

$$WWA = -ABC.AAC.ABE \quad \text{etc.}$$

Again all terms were calculated using program 1.

For the lateral displacement, sway is defined by



The transfer function is

$$\frac{Y}{\delta} = \frac{WWA.S + (WWC + VVA)S + (WWF + VVC)S + WVB + VVF}{SSA.S^5 + SSB.S^4 + (SSE + SSA)S^3 + (SBS + SSB)S^2 + (SES + SSE)S + SBS.S + SES.S}$$

(25)

A. MANUALLY STEERED SHIP MOTION

As mentioned before, the goal of this section is to get the ship trajectories in constant wind effect with low ship speed. For this purpose computer program (II) was developed and applied to equation (20). Two situations were considered:

Situation 1: zero degree rudder deflection (unsteered).

Situation 2: positive 15 degree rudder deflection.

All these situation were studied assuming that the ship moved in the forward direction at a 1 mile/hr speed in a calm sea. Each of the wind velocities was applied suddenly.

Computer program II responses are shown in Figures 5 through 30 for yaw and sway. These results were also tabulated in Tables 1 through 4. The first test on the unsteered

situation is shown in the computer outputs from Figure 5 to Figure 24 for three different wind directions and various velocities. Tabulated values are shown on Table 1 and 2, for yaw and sway.

The effects are examined by referring to the tables.

Case 1: Head Wind

As is shown in Tables 1 and 2 and Figures 5 - 10, effects of the head wind were small on the straight forward ship motion. In this test, a 5 mile/hr wind velocity is applied to the ship which created -10^{-3} rad. variation on the course and drift was -7.4×10^{-3} ft. in 5 minutes.

Case 2: Beam Wind

Secondly, beam wind disturbances were examined for various velocities. According to Tables 1 and 2 and Figures 11 -16, the ship greatly deflected from a straight course where the wind velocity exceeded 5 miles/hr. Deviation was positive 22 degree (.395 rad) on the straight course and positive 9.2 ft drift in 5 minutes when the 7 miles wind velocity was applied, as shown in Figures 15 and 16.

Case 3: Stern Wind

In this part, the ship was disturbed with stern wind which created great difficulty on the straight course. Five miles/hr wind velocity created -2.29 degree (-.04 rad) deviation and -.28 feet drift in 5 minute. But 7 miles/hr wind velocity causes the ship to deviate by -332.3 degree from the straight course in 4 minute 10 second. Drift was -110 ft in 4 minute but this value was reduced to -15 ft in 5 minute.

<u>Figure</u>	<u>Wind Direction (degree)</u>	<u>Wind Velocity (miles)</u>	<u>Time (sec)</u>	<u>Yaw (rad.)</u>
	0	1	300	-3×10^{-4}
	180	1	300	-14×10^{-4}
	0	3	300	-7.5×10^{-4}
	180	3	{ 50 300	{ -9×10^{-4} -6.5×10^{-4}
	90	3	300	2×10^{-4}
	0	5	{ 100 300	{ -2×10^{-3} -1.4×10^{-3}
	180	5	300	-4×10^{-2}
	90	5	300	8×10^{-3}
	180	7	300	-5.8
	90	7	300	0.395

Table 1. Variation of Yaw for Unsteered Ship.

<u>Figure</u>	<u>Wind Direction (degree)</u>	<u>Wind Velocity (miles)</u>	<u>Time (sec)</u>	<u>Sway (ft)</u>
	0	1	300	-2.9×10^{-3}
	180	1	300	$-.5 \times 10^{-4}$
	0	3	300	-6.2×10^{-4}
	180	3	$\begin{Bmatrix} 80 \\ 300 \end{Bmatrix}$	$\begin{Bmatrix} 0.0 \\ -4.4 \times 10^{-3} \end{Bmatrix}$
	90	3	300	2.7×10^{-3}
	0	5	300	-7.4×10^{-3}
	180	5	300	$-.28$
	90	5	300	6.2×10^{-2}
	180	7	$\begin{Bmatrix} 250 \\ 300 \end{Bmatrix}$	$\begin{Bmatrix} -110. \\ -15. \end{Bmatrix}$
	90	7	300	9.2

Table 2. Variation of Sway for Unsteered Ship.

1891

1892

1893

1894

1895

1896

1897

1898

1899

Briefly the system was unstable and the ship was turned around. There is no chance to control the ship. Drift was negative 110 ft in 4 minute but this value was reduced the negative 15 ft in 5 minute. The summarization of this test can be stated as the following: computer program (II) responses were tabulated for 3 different wind directions and various velocities. According to the table, wind disturbance was not so important on the course from any direction until 5 miles/hr wind velocity was reached. Critical points were 5 and 7 miles/hr wind velocities for stern and beam wind respectively.

Second test: 15 degree rudder displacement was applied under the beam and stern wind disturbances. The main purpose was to show the effect of the rudder displacement on the ship course with wind. As is known, positive rudder displacement causes negative yaw. All responses are shown in Figures 25-30 and tabulated values are shown in Tables 3 and 4. According to the Tables 3 and 4, when the ship is effected 5 miles beam wind velocity and positive 15 degree rudder displacement. So, ship was deflected -327 degree from the original path in 5 minute. Drift was 80 ft in 2.5 minute and -100 ft in 5 minute. As mentioned earlier, 5 miles/hr beam wind with zero rudder displacement has created 8×10^{-3} rad. deviation from the original path, as shown in Table 1. But the same condition with 15° rudder displacement has -327° deviation from the original path. In this case, the ship was so effected with rudder force and started to turn around the path.

<u>Figure</u>	<u>WD.DI. (degree)</u>	<u>WD.VEL. (miles)</u>	<u>Time (sec)</u>	<u>Yaw (rad)</u>
	180	3	300	-4
	180	5	300	-18
	90	5	300	-5.7

Table 3. Variation of Yaw for Manually Steered Ship ($S=15^\circ$).

<u>Figure</u>	<u>WD.DI. (degree)</u>	<u>WD.VEL. (miles)</u>	<u>Time (sec)</u>	<u>Sway (ft)</u>
	180	3	{ 85 240	{ 9 -18
	180	5	nonlinear oscillation	
	90	5	{ 150 300	{ 80 -100

Table 4. Variation of Sway for Manually Steered Ship ($S=15^\circ$).

The other situation is a stern wind disturbance with 15° rudder displacement. Also known from Table 1, 5 miles/hr stern wind velocity with zero rudder displacement has created $-.04$ rad. deviation from the original path. In this case, 15 degree rudder displacement created $-.18$ rad. deviation in 5 minute. Ship was turned 360° around the course in 2 minute and drifted with divergent oscillation.

All these tests were made with ship speed being 1 mile/hr in the calm water and values of wind velocities were suddenly applied.

B. AUTOMATICALLY STEERED SHIP

Earlier tests show that the ship was effected by wind and rudder.

In this section, another test was developed to minimize the deviation from the original path. For this reason rudder deflection is used and is written as a function of ψ .

The equation for the rudder deflection is:

$$\bar{\delta} = \alpha \dot{\bar{\delta}} + \bar{\delta} = k_t \dot{\psi} + k\psi$$

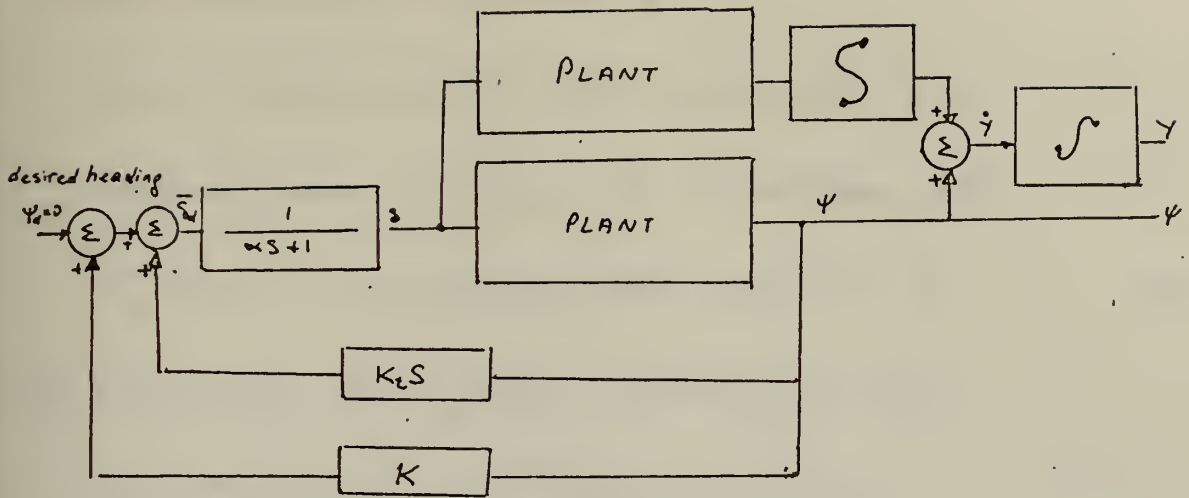
where

α = rudder response time constant (time lag)

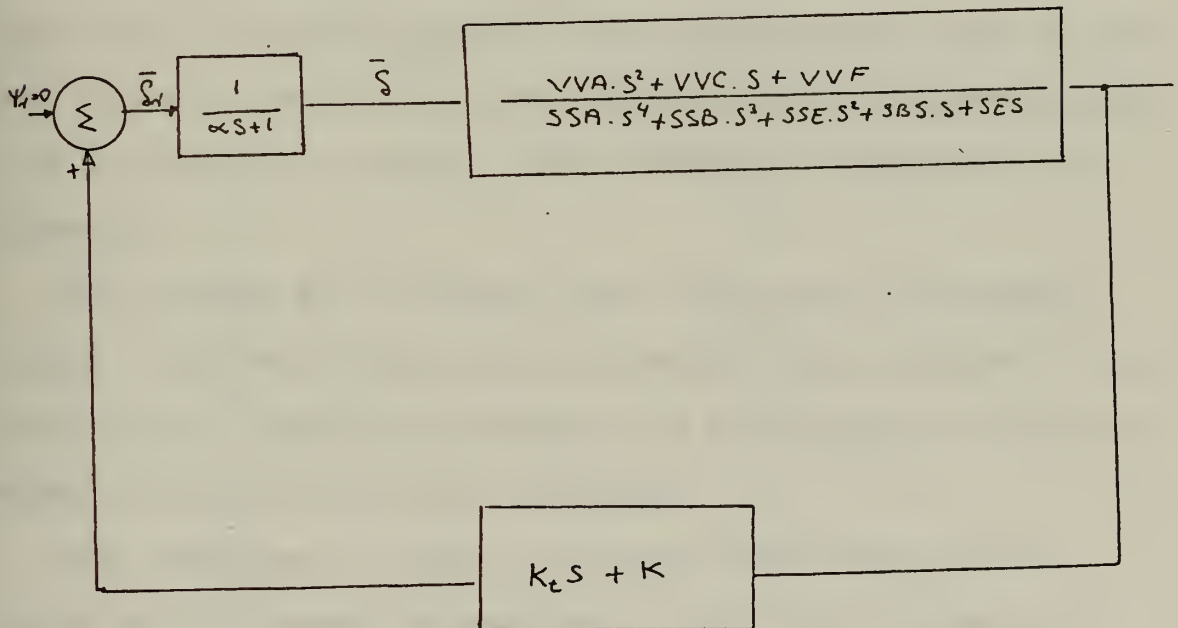
k = yaw gain constant

k_t = yaw rate gain constant

Thus, the system would be:



These control effectors are the function of some parameter that could be measured by sensors, usually a motion parameter.



Let

$$\frac{1}{\alpha} = \alpha_1$$

$$G = \frac{\psi}{\delta d} = \frac{VVA \cdot S^2 + VVC \cdot S + VVF}{SSA \cdot S^4 + SSB \cdot S^3 + SSE \cdot S^2 + SBS \cdot S + SES} \cdot \frac{\alpha_1}{S + \alpha_1} \quad (26)$$

$$H = K + K_t S$$

So the characteristic equation is

$$\begin{aligned} & SSA \cdot S^5 + (SSB + \alpha_1 / SSA) \cdot S^4 + (SSE + \alpha_1 SSB - \alpha_1 \cdot VVA \cdot K_t) S^3 \\ & + (SBS + \alpha_1 \cdot SSE - \alpha_1 \cdot VVC \cdot K_t - \alpha_1 \cdot VVA \cdot K) S^2 + (SES + \alpha_1 \cdot SBS \\ & - \alpha_1 \cdot VVF \cdot K_t - \alpha_1 \cdot VVC \cdot K) S + (\alpha_1 \cdot SES - \alpha_1 \cdot VVF \cdot K) = 0 \end{aligned} \quad (27)$$

For simplicity, let $B_1 = SSA$, $B_2 = SSB + \alpha_1 \cdot SSA$ etc.

$$\begin{aligned} & B_1 \cdot S^5 + B_2 S^4 + (B_3 - B_4 \cdot K_t) S^3 + (B_5 - B_6 \cdot K_t - B_7 K) S^2 \\ & + (B_8 - B_9 \cdot K_t - B_{10} \cdot K) S + (B_{11} - B_{12} \cdot K) = 0 \end{aligned} \quad (28)$$

This characteristic equation was calculated using computer program 1. Computer program III was used to get transient responses in yaw and sway for the automatically steered ship. Each curve of yaw or sway was developed with different parameter values (for K and K_t), for different wind speed and direction.

The problem is to minimize the variation on the ship course. For this reason, the parameter plane program is applied to the system to determine the best value of yaw gain constant and yaw rate gain constant.

The responses of these are shown from Figure 40 to Figure 44 for several situations. The values chosen are the minimum values shown on the curves according to reference [6].

The parameter plane outputs are developed by applying equation (27) to program IV. Table 5 shows the best values

<u>Wind Direction</u>	<u>Wind Velocity</u>	<u>K</u>	<u>Kt</u>
000	1	2.493	3.53
000	3	2.327	3.712
000	5	4.994	3.722
090	3	3.945	3.480
180	1	3.425	3.577

Table 5. Yaw Gain Constant and Yaw Rate Gain Constant Values for Several Wind Directions and Velocities (which were found from parameter plane computer outputs).

of the yaw gain constant and yaw rate gain constant for the automatically steered ship.

All responses of the automatically steered ship are shown in Figure 31 through 33 and tabulated on Tables 6 and 7.

According to the Tables (6 and 7), the variations on the course is minimized for the low wind velocities. In the head wind disturbance, course variations were reduced to 0 rad. in 5 minute.

One mile/hr wind velocity response reached 0 rad. in 20 sec., 3 mile/hr gave 0 rad. response in 65 sec. But 5 miles/hr wind velocity response was 1×10^{-4} rad. in 5 minute.

For the beam wind effect, 3 miles/hr wind velocity was applied to the ship. Deviation was 0 rad. in 70 sec.

A stern wind was also tried, 1 mile/hr wind velocity caused a deviation which was corrected to 0 rad. in 65 sec.

As is seen above, the ship trajectory was kept on the original path. This desired course or original path was assumed to be due North. Also the same test condition was applied.

<u>Figure</u>	<u>WD.DI. (degree)</u>	<u>WD.VEL. (miles)</u>	<u>Time(sec)</u>	<u>Yaw(rad)</u>
	0	1	{ 10 300	{ -1×10^{-4} ~0
	180	1	{ 50 300	{ -1×10^{-4} ~0
	0	3	{ 15 300	{ -1×10^{-4} ~0
	90	3	{ 20 300	{ $.85 \times 10^{-4}$ ~0
	0	5	{ 30 300	{ 1×10^{-4} $.5 \times 10^{-4}$

Table 6. Variation of Yaw for Automatically Steered Ship.

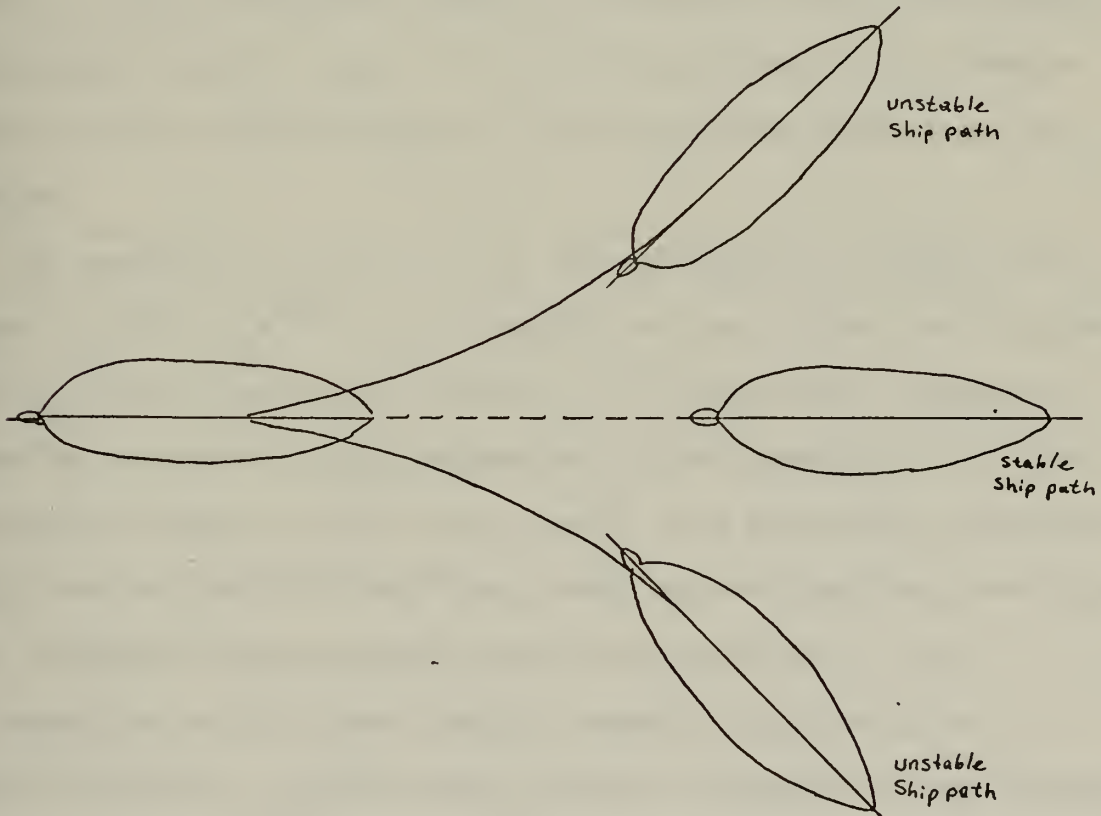
<u>Figure</u>	<u>WD.DI. (degree)</u>	<u>WD.VEL. (miles)</u>	<u>Time(sec)</u>	<u>Sway(ft)</u>
	0	1	300	10×10^{-4}
	180	1	300	13×10^{-3}
	0	3	300	11.5×10^{-4}
	90	3	300	-5×10^{-3}

Table 7. Variation of Sway for Automatically Steered Ship.

IV. STABILITY ANALYSIS

Stability may be defined in the following way. Establish an equilibrium situation, disturb the equilibrium condition with arbitrary disturbances. If the ship returns or tends to return to the original straight-line condition of equilibrium after a disturbance of the smallest amount (infinitesimal disturbance), it is stable. If it departs or has the tendency to depart from the original straight-line equilibrium condition, it is unstable.

The unstable ship will go in to a starboard or port turn.



Stability analysis is performed by solving for the eigen values of the system matrix (4 x 4) which is defined on page 46. Reference [3] contains straight forward algebraic solution of the linearized equations. According to reference [3] a complete algebraic solution of linearized equation (20) is obtained with a differential operator. Solution result of any independent variable X_j is defined as:

$$X_j(t) = C_{1j}e^{\sigma_1 t} + C_{2j}e^{\sigma_2 t} + \dots + C_{mj}e^{\sigma_m t}$$

$$X_j(t) = \sum_{i=1}^m C_{ij} e^{\sigma_i t} \quad (29)$$

Where C_{ij} are arbitrary constants depending upon the initial conditions and $\sigma_1, \sigma_2, \dots, \sigma_m$ are the roots of the determinant of the coefficients in the linearized equations of motion.

In general $\sigma_1, \sigma_2, \dots, \sigma_m$ are different in value, the terms $C_1 e^{\sigma_1 t}, C_2 e^{\sigma_2 t}, \dots, C_m e^{\sigma_m t}$ can not negate one another. The only way that each term can go to zero with increasing time is for each of the exponents to be negative. If σ is a complex number in the form $\sigma = a + ib$, the following relationship hold $e^{\sigma t} = e^{(a+ib)t} = e^{at}(\cos bt + i \sin bt)$ and the condition for stability requires that the real parts of $\sigma_1, \sigma_2, \dots, \sigma_m$ be negative as they are complex numbers (the imaginary σ , parts of number indicate the angular frequency of oscillation). The Routh criterion can also be applied to determine system stability. If we look at equation (20) again, the automatically steered ship equation would be:

$$ABC.\ddot{\bar{\psi}}-AAD.\dot{\bar{\psi}}-BFA.\bar{\psi}-BGC.\bar{V}-BGD.\bar{U} = AAE.\bar{S}$$

$$-BGE.\dot{\bar{\psi}}-BFD\bar{\psi} + ABD.\dot{\bar{V}}-BGF \bar{V}-BGG \bar{U} = AAC.\bar{S}$$

$$-CAA.\dot{\bar{\psi}}-BFG\bar{\psi}- BGA.\bar{V}+ABE.\dot{\bar{U}}-CAB.\bar{U} = CAC.\bar{S}$$

$$QQQ.\dot{\bar{\psi}}+QQO.\bar{\psi} = QQQ.\dot{\bar{S}} + \bar{S} \quad (30)$$

Where

$$QQO = k_t, \quad QQQ = k, \quad QQQ = tr = \alpha$$

Equation (30) will be written in the following way.

ABC	-AAD	-BFA	0	-BGC	0	-BGD	0	-AAE
0	$\ddot{\bar{\psi}}+$	$\dot{\bar{\psi}}+$	$\bar{\psi}+$	ABD	$\dot{\bar{V}}+$	$\bar{V}+$	$\dot{\bar{U}}+$	$\bar{U}+$
0	-BGE	-BFD	0	-BGF	0	-BGG	0	$\dot{\bar{\xi}}+$
0	-CAA	-BFG	0	-BGA	ABE	-CAB	0	-CAC
0	QQO	QQQ	0	0	0	0	-QQQ	-1

(31)

As is seen from equation (31) there are four independent variables namely yaw, sway, surge and the rudder angle. The form used in equation (29) is applied.

$$\bar{\psi} = \sum_{i=1}^m \bar{\psi}_i e^{\sigma_i t}, \quad \bar{V} = \sum_{i=1}^m \bar{V}_i e^{\sigma_i t}, \quad \bar{U} = \sum_{i=1}^m \bar{U}_i e^{\sigma_i t}, \quad \bar{S} = \sum_{i=1}^m \Delta_i e^{\sigma_i t} \quad (32)$$

Where $\bar{\psi}_i$, \bar{V}_i , \bar{U}_i and Δ_i are arbitrary constants.

Substitution of equation (32) into equation (31):

$ABC\sigma_i^2 - AAD.\sigma_i - BFA$	-BGC	-BGD	-AAE
$-BGE\sigma_i - BFO$	$ABD\sigma_i - BGF$	-BGG	-AAC
$-CAA\sigma_i - BFG$	-BGA	$ABE\sigma_i - CAB$	-CAC
$QQO\sigma_i + QQQ$	0	0	$-QQQ\sigma_i - 1$

(33)

Solutions of equation (33) are possible for only values of σ_i which satisfy equation (34).

$$\begin{vmatrix} (ABC\sigma_i^2 - AAD\sigma_i - BFA) & (-BGC) & (-BGD) & (-AAE) \\ (-BGE\sigma_i - BFD) & (ABD\sigma_i - BGF) & (-BGG) & (-AAC) \\ (-CAA\sigma_i - BFG) & (-BGA) & (ABE\sigma_i - CAB) & (-CAC) \\ (QQQ\sigma_i + QOQ) & 0 & 0 & (-QQQ\sigma_i - 1) \end{vmatrix} = 0 \quad (34)$$

Program I gives the solution of this equation as fifth order polynomial. For different situations such as wind velocity and direction other polynomials were also found. As is pointed out in page , it is important for the real root to be negative for system stability.

This test was examined in two situations:

Situation 1: constant wind directions with varied velocities.

Situation 2: constant wind velocities with varied direction.

The first situation was divided into 3 sections:

Section a: constant head wind with several velocities.

Section b: constant beam wind with several velocities.

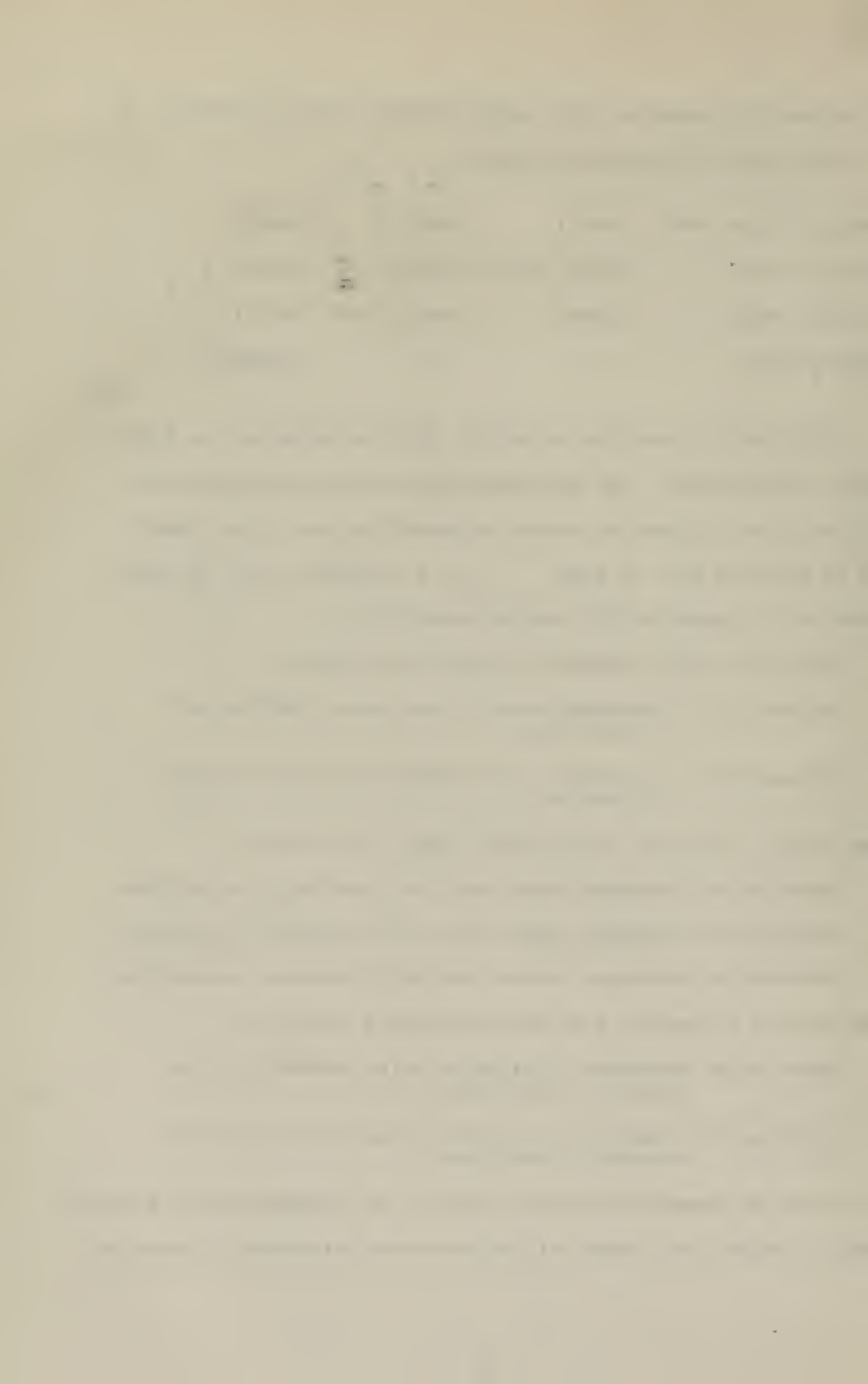
Section c: constant stern wind with several velocities.

The second situation was divided into 2 section:

Section a: constant 7 miles/hr wind velocity with several directions.

Section b: constant 9 miles/hr wind velocity with several directions.

In order to examine the stability of an automatically steered ship in wind, all these situations are solved with computer



program I, tabulated on Tables 8 - 12 and drawn on the CALCOMP plotters, from Figures 45 through 49.

Situation 1: This test was developed, constant wind direction disturbed the ship. Wind velocities changed each time.

a) Head wind disturbance:

As is shown in Table 8 and Figure 45, the ship would be stable in varied head wind velocities until 13 miles/hr wind velocity. After this range, the ship could be unstable on the horizontal plane.

b) Beam wind disturbance:

In this case, the stability range was shorter (from 1 to 8 miles/hr). After the 8 miles/hr wind velocities the ship could be strictly unstable, shown on Table 9 and Figure 46.

c) Stern wind disturbance:

Stern wind effect on the stability might be the shortest range, as shown on Figure 47 and Table 10. This range included from 1 to 6 miles/hr. After 6 miles/hr wind velocities, the ship could be unstable.

Situation 2: In this case, constant wind velocity disturbed the ship. Wind direction was changed for each test.

a) In 7 miles/hr wind velocity with varied direction. From 0 degree through 180 degree wind directions were tried in 7 miles/hr wind velocity. According to Table 11 and Figure 48, the ship could be unstable when the wind disturbed the ship from 30 degree, 105 degree and 180 degree

wind direction. In the other wind direction and 7 miles/hr wind velocity the ship trajectory could be stable.

b) In 9 miles/hr wind velocity with varied wind direction. As is shown on Figure 49 and Table 12, 9 miles/hr wind velocity with each direction were applied to the system. The ship could be stable when the wind direction was head, 60 degree - 75 degree and 120 degree - 135 degree. For the rest of the directions (0° - 180°) the ship trajectory was unstable.

All of these results show that some of the wind directions and velocities played a very active role. These directions are 30 degree, 105 degree and 180 degree. After the 9 miles/hr wind velocities, many of the wind directions had adverse affects on stability.

Head Wind

Ua	Re σ_1	Re σ_2	Re σ_3	Re σ_4	Re σ_4
5	-8.8	-.111	-6.35×10^{-3}	-12.11	-59.97
6	-8.17	-.117	-9.87×10^{-3}	-11.33	-60.37
7	-7.21	-.124	-1.39×10^{-2}	-11.11	-60.25
8	-6.2	-.13	-1.88×10^{-2}	-10.8	-60.34
9	-5.1	-.138	-2.4×10^{-2}	-10.7	-60.28
10	-3.93	-.148	-2.98×10^{-2}	-10.48	-60.41
11	-2.67	-.162	-3.6×10^{-2}	-10.61	-60.02
12	-1.49	-.189	-4.2×10^{-2}	-10.42	-60.35
13	-4.25×10^{-2}	-.2	-.2	-10.46	-60.09
14	+ .964	$-.84 \times 10^{-1}$	$-.84 \times 10^{-1}$	-10.4	-60.4

Table 8. Real Roots of Characteristic Equation.

Beam Wind

Ua	Re σ_1	Re σ_2	Re σ_3	Re σ_4	Re σ_5
1	-9.72	-0.091	-6.4×10^{-4}	-16.3	-59.9
2	-9.65	-0.034	-7.5×10^{-4}	-14.6	-60.66
3	-8.97	-0.099	-9.1×10^{-4}	-13.37	-60.06
4	-8.8	-0.105	-1.46×10^{-3}	-11.1	-55.99
5	-6.76	-0.115	-2.76×10^{-3}	-10.9	-60.25
6	-4.7	-0.129	-4.94×10^{-3}	-10.47	-60.7
7	-2.56	-0.148	-7.8×10^{-3}	-10.4	-60.4
8	-4.6×10^{-3}	-0.239	-0.239	-10.3	-60.2
9	+1.94	-0.025	-0.148	-10.25	-60.4
10	+4.25	-0.029	-0.186	-10.22	-60.42

Table 9. Real Roots of Characteristic Equation.

Stern Wind

<u>Ua</u>	<u>Re σ_1</u>	<u>Re σ_2</u>	<u>Re σ_3</u>	<u>Re σ_4</u>	<u>Re σ_5</u>
1	-9.3	-.09	-4.5×10^{-4}	-13.3	-60.3
2	-8.7	-.0978	-2.43×10^{-4}	-11.7	-60.48
3	-7.3	-.0894	-1.84×10^{-3}	-11.2	-59.95
4	-5.56	-.087	-5.2×10^{-3}	-10.7	-60.14
5	-3.6	-.084	-1.1×10^{-2}	-10.5	-60.3
6	-1.57	-.085	-1.85×10^{-2}	-10.36	-60.47
7	+4.43	-.0296	-.0296	-10.286	-60.62
8	+2.57	-.0468	-.0468	-10.24	-60.53
9	+4.67	-.054	-.054	-10.21	-60.55
10	+6.77	-.064	-.064	-10.19	-60.56

Table 10. Real Roots of Characteristic Equation.

<u>WD.DI.</u>	<u>Re σ_1</u>	<u>Re σ_2</u>	<u>Re σ_3</u>	<u>Re σ_4</u>	<u>Re σ_5</u>
0°	-7.21	-.124	-.014	-11.11	-60.25
30°	+3.46	-.0104	-.138	-10.215	-60.44
45°	-3.34	-.082	-.0114	-16.42	-60.38
60°	-4.9	-.088	-.035	-10.63	-60.3
75°	-4.92	-.145	-.0143	-10.6	-60.26
90°	-2.56	-.148	-7.8×10^{-3}	-10.4	-60.4
105°	+3.16	-.0419	-.419	-10.2	-60.56
120°	-6.22	-.0896	-.0153	-10.8	-60.29
135°	-6.56	-.118	-.0249	-10.92	-60.28
150°	-.0113	-.947	-.198	-10.331	-60.364
165°	-1.6×10^{-3}	-.956	-.155	-10.3	-60.44
180°	+.443	-.0286	-.0286	-10.286	-60.62

Table 11. Real Roots of Characteristic Equation, Wind Velocity = 7 miles.

<u>WD.DI.</u>	<u>Re σ_1</u>	<u>Re σ_2</u>	<u>Re σ_3</u>	<u>Re σ_4</u>	<u>Re σ_5</u>
0°	-5.08	-.138	-.024	-10.68	-60.28
30°	+8.53	-.19	-.0238	-10.16	-60.1
45°	+.1054	-1.25	-.0275	-7.85	-60.8
60°	-2.25	-.073	-.0732	-10.4	-60.36
75°	-2.14	-.193	-.0224	-10.42	-60.33
90°	+1.94	-.027	-.145	-10.25	-60.42
105°	+8.14	-.056	-.056	-10.16	-60.62
120°	-3.07	-.07	-.045	-10.45	-60.42
135°	-4.31	-.132	-.038	-10.55	-60.34
150°	+2.8	-.0368	-.17	-10.24	-60.4
165°	+4.1	-.0128	-.146	-10.2	-60.47
180°	+4.67	-.054	-.054	-10.21	-60.55

Table 12. Real Roots of Characteristic Equation, Wind Velocity = 9 miles.

V. DISCUSSION OF RESULTS AND CONCLUSIONS

The procedures for system course control and stability analysis on the horizontal plane were described. Applying the datas which are taken from some references, to the three degree freedom equation gave us course control and stability analysis computer outputs. As a result of these outputs some comments can be made. First of all the unsteered case was examined. It is seen that the stern wind effects the straight course of the ship the most. When the wind velocity reaches 7 miles/hr this effect becomes extremely high. In 5 minutes, the deviation of the course is about 327 degree. At the same time the effect of the head wind on the straight course compared to the stern and beam wind seems to be much less; which is seen from the computer outputs.

To see the effect of the rudder deflection on the straight course there should be positive 15 degree applied to the rudder for beam and stern wind. Under these conditions negative yaw and sway were found. When the ship is under stern wind, applying positive 15 degree rudder deflection will create extremely negative yaw and sway. As it is seen in Figures 29 and 30, when the stern wind velocity reaches 5 miles in 50 seconds, 15 degree rudder deflection will create minus 145 degree deviation from the course.

Computer output results were also obtained for an automatically steered ship. Parameter plane computer programs were applied to the closed loop system for choosing the best value of yaw rate gain constant and yaw gain constant. According to the automatically steered ship computer outputs, in low wind speeds the course variation is minimized. Sway can't be controlled very well but the value of the drift has decreased compared to the unsteered case.

In a final study, using the eigen value theorem, system stability and the critical wind velocity are found and tabulated. Computed results show that 30 degree, 105 degree and 180 degree wind direction are important on the ship course in \bar{X} miles/hr wind velocities. Also 9 miles/hr wind velocity in many direction were so effected.

All the studies done above are made for a ship which has a speed of 1 mile/hr and limited special full loaded ship form.

APPENDIX

Hydrodynamic and aerodynamic coefficients where used in equation (5)

$$\begin{aligned}
 A_1 &= \frac{e}{2} \ell^5 N_{r'} & B_1 &= \frac{e}{2} \ell^3 Y_{v'} & C_1 &= \frac{e}{2} \ell^3 X_{v'} \\
 A_2 &= \frac{e}{2} \ell^3 N_{v'} & B_2 &= \frac{e}{2} \ell^2 Y_{v'} & C_2 &= \frac{e}{2} \ell^2 X_{o'} \\
 A_3 &= \frac{e}{2} \ell^4 N_{r'} & B_3 &= \frac{e}{2} \ell^3 Y_{r'} & C_3 &= \frac{e}{2} \ell^3 X_{vv'} \\
 A_4 &= \frac{e}{2} \ell^3 N_{s'} & B_4 &= \frac{e}{2} \ell^2 Y_{s'} & C_4 &= \frac{e}{2} \ell^2 X_{ss'}
 \end{aligned}$$

Where

A_i = Coefficients of hydrodynamic moment in yaw

B_i = Coefficients of hydrodynamic forces in sway

C_i = Coefficients of hydrodynamic forces in surge

$i = 1, 2, 3, 4$

N_1, N_2, Y_1, X_1 are coefficients of aerodynamic forces and moments

Aerodynamic forces and moment

$$X_A' = \frac{X_a}{\frac{ea}{2} \ell^2 U a^2} = X_{i'} U_{a'} = X_{a1'} \cos \psi a$$

$$N_A' = \frac{N_a}{\frac{ea}{2} \ell^3 U a^2} = N'u'v' + N'v' = \frac{Na_1'}{2} \sin 2\psi a + Na_2' \sin \psi a$$

$$Y_A' = \frac{Y_a}{\frac{ea}{2} \ell^2 U a^2} = Y_{1'} V_{a'} = Y_{a1'} \sin \psi a$$

Which

$$x_1' = x_{a_1}' = -0.015$$

$$y_1' = y_{a_1}' = -0.056$$

$$N_1' = N_{a_1}' = -0.0046, \quad N_2' = -N_{a_2}' = -0.017$$

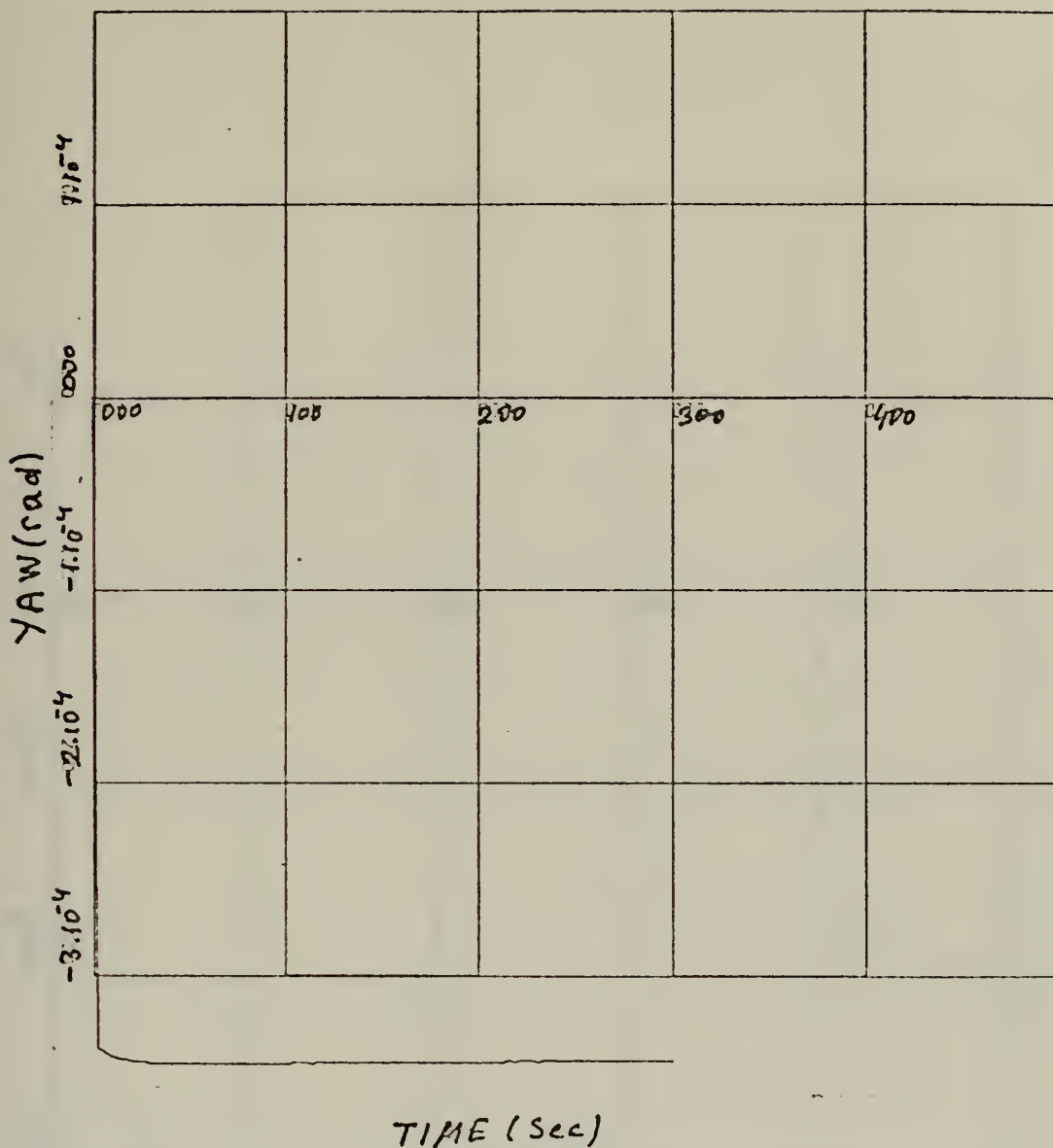


Figure 5. Variation of Yaw Versus Time for Wind Direction 000°, Velocity 1 mile/hr.

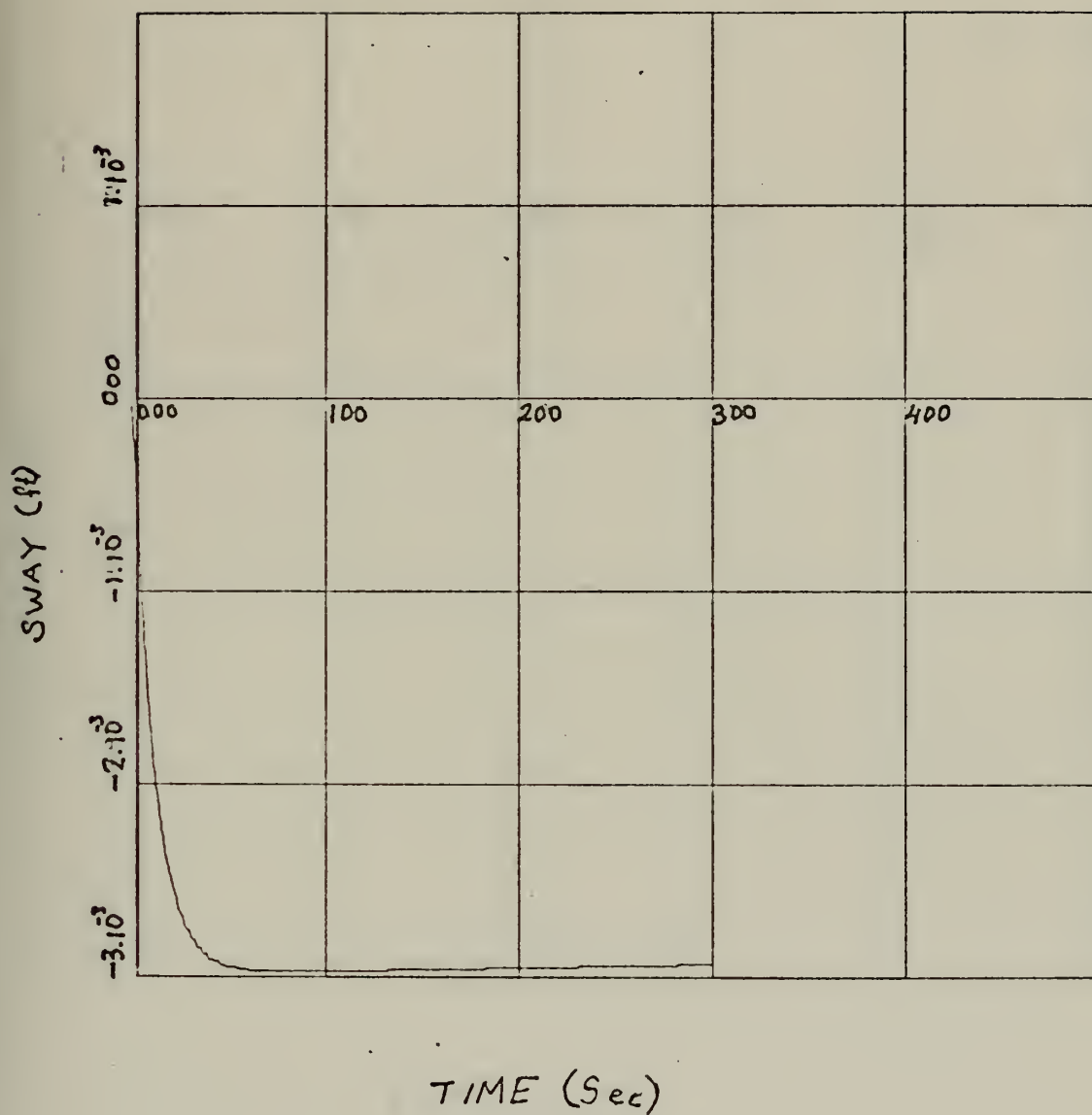


Figure 6. Variation of Sway Versus Time for Wind Direction 000° , Velocity 1 mile/hr.

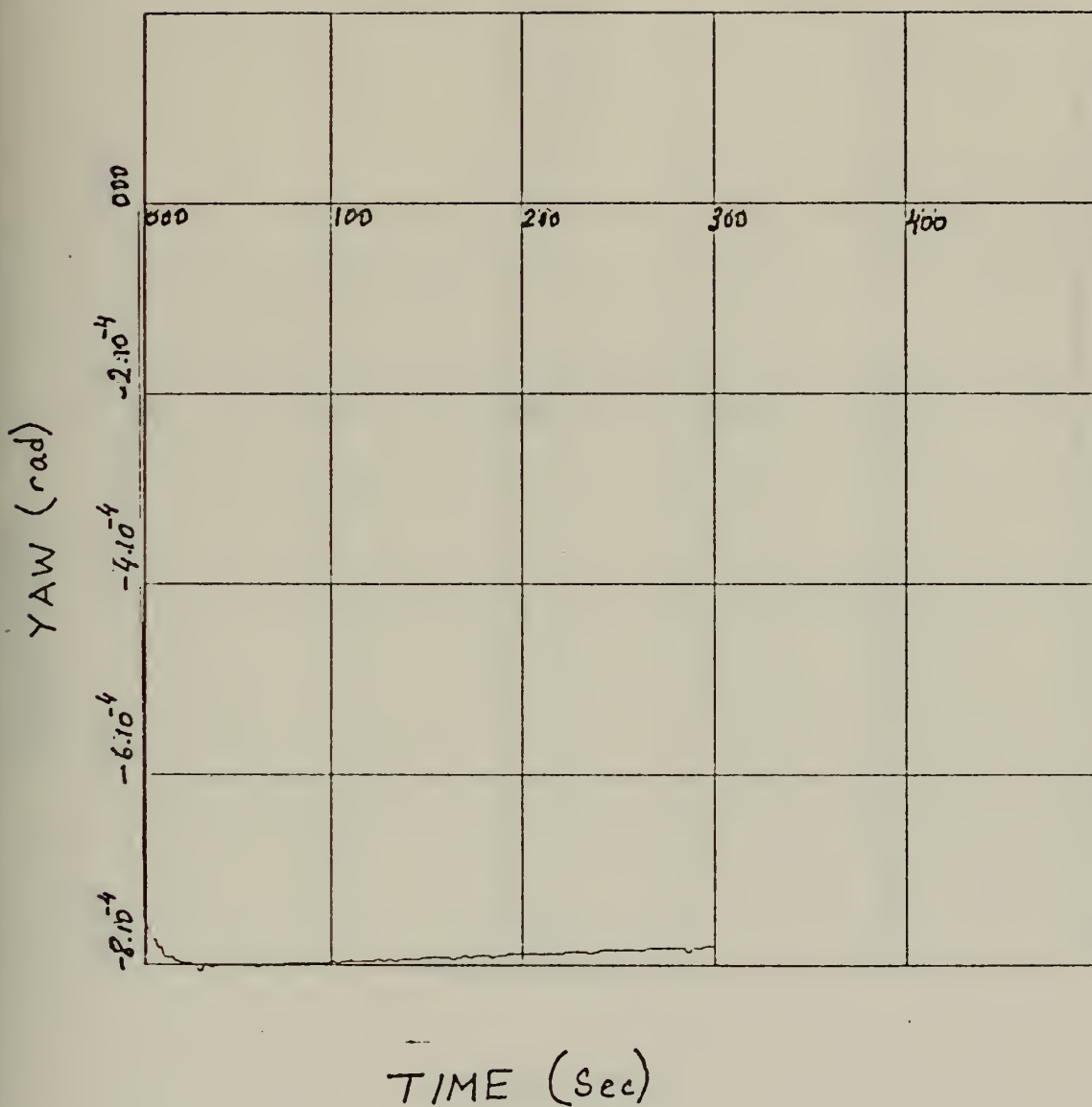


Figure 7. Variation of Yaw Versus Time for Wind Direction 000° , Velocity 3 miles/hr.

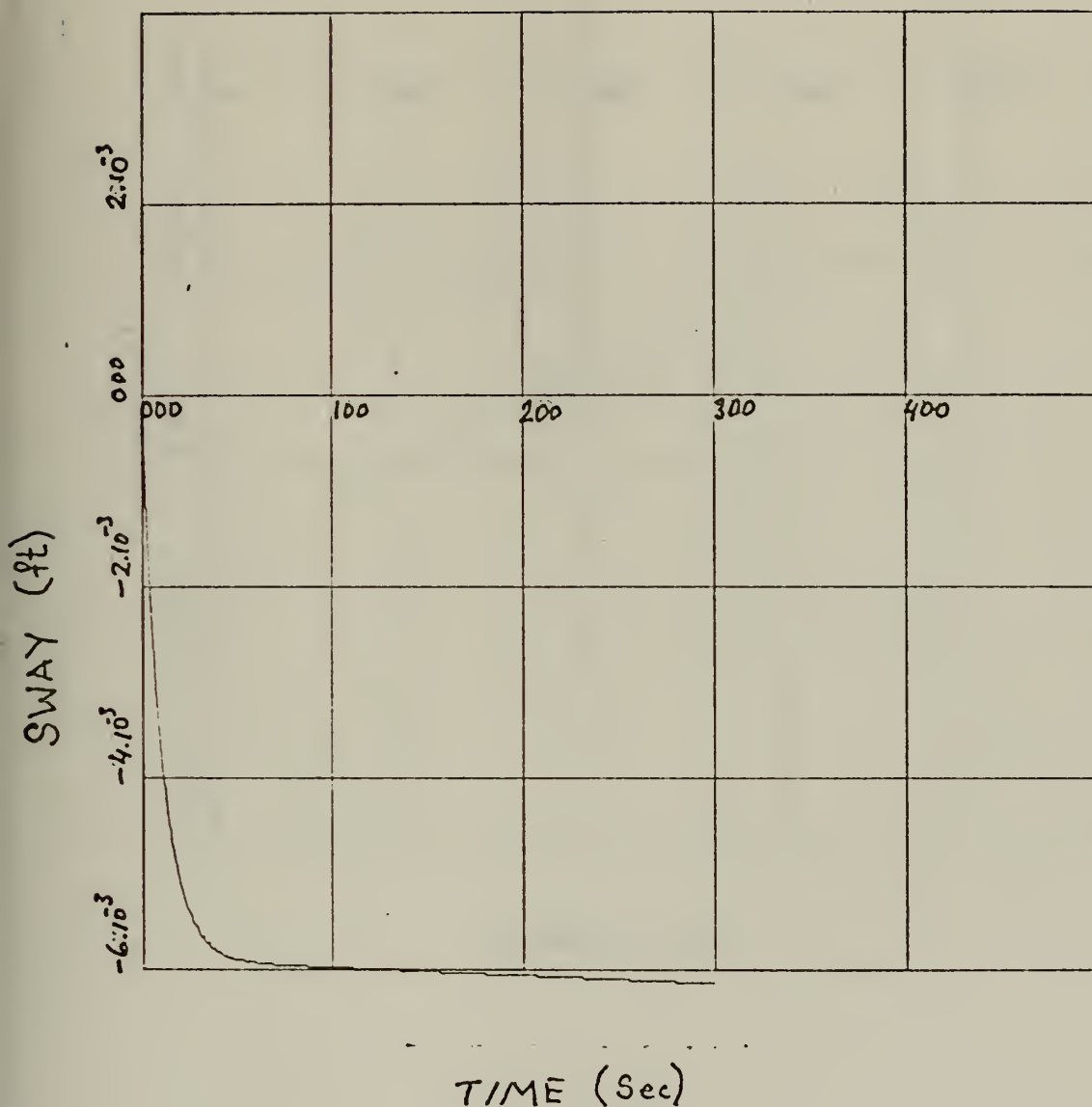


Figure 8. Variation of Sway Versus Time for Wind Direction 000°, Velocity 3 miles/hr.



Figure 9. Variation of Yaw Versus Time for Wind Direction 000° , Velocity 5 miles/hr.



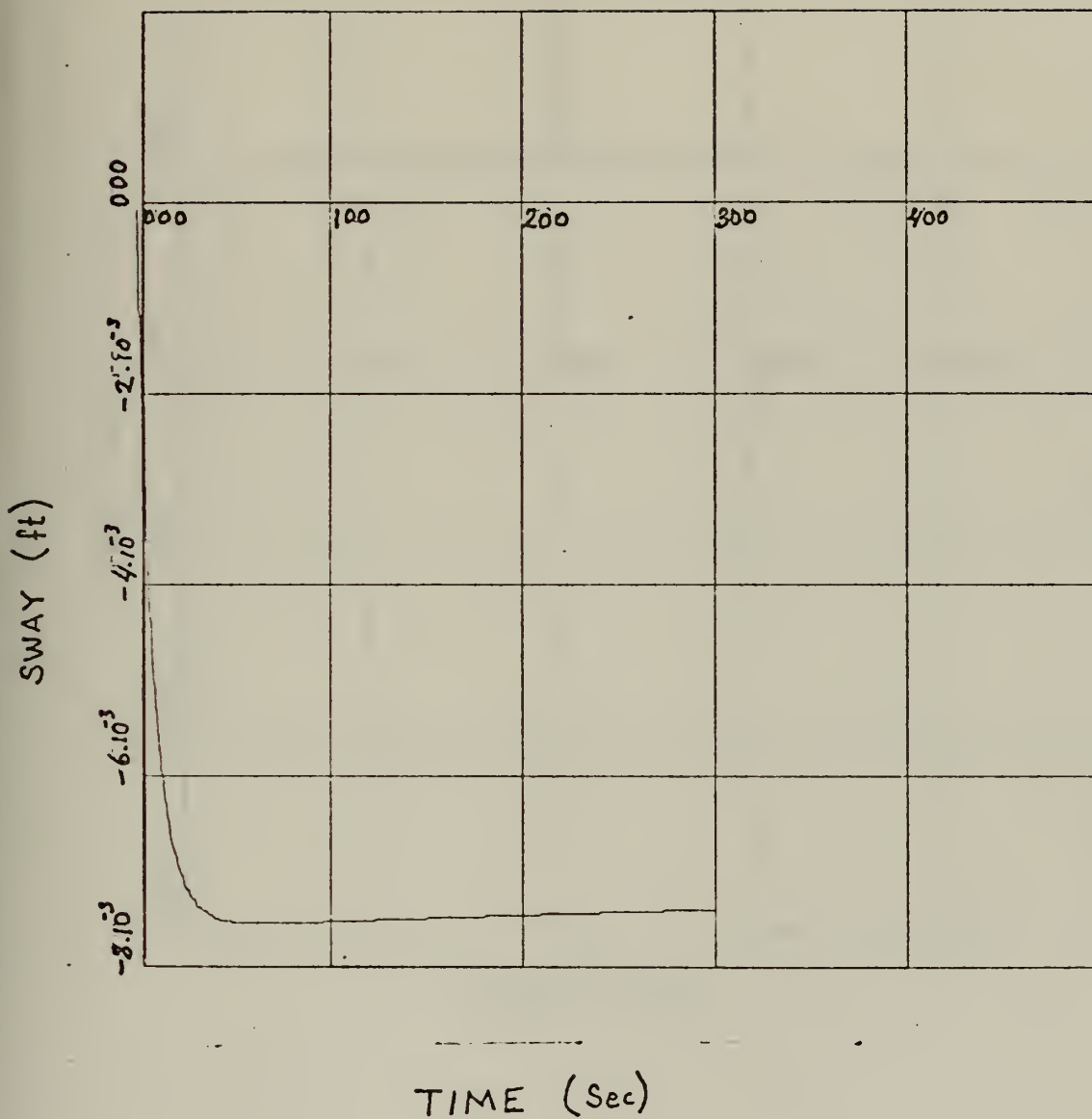


Figure 10. Variation of Sway Versus Time for Wind Direction 000°, Velocity 5 miles/hr.

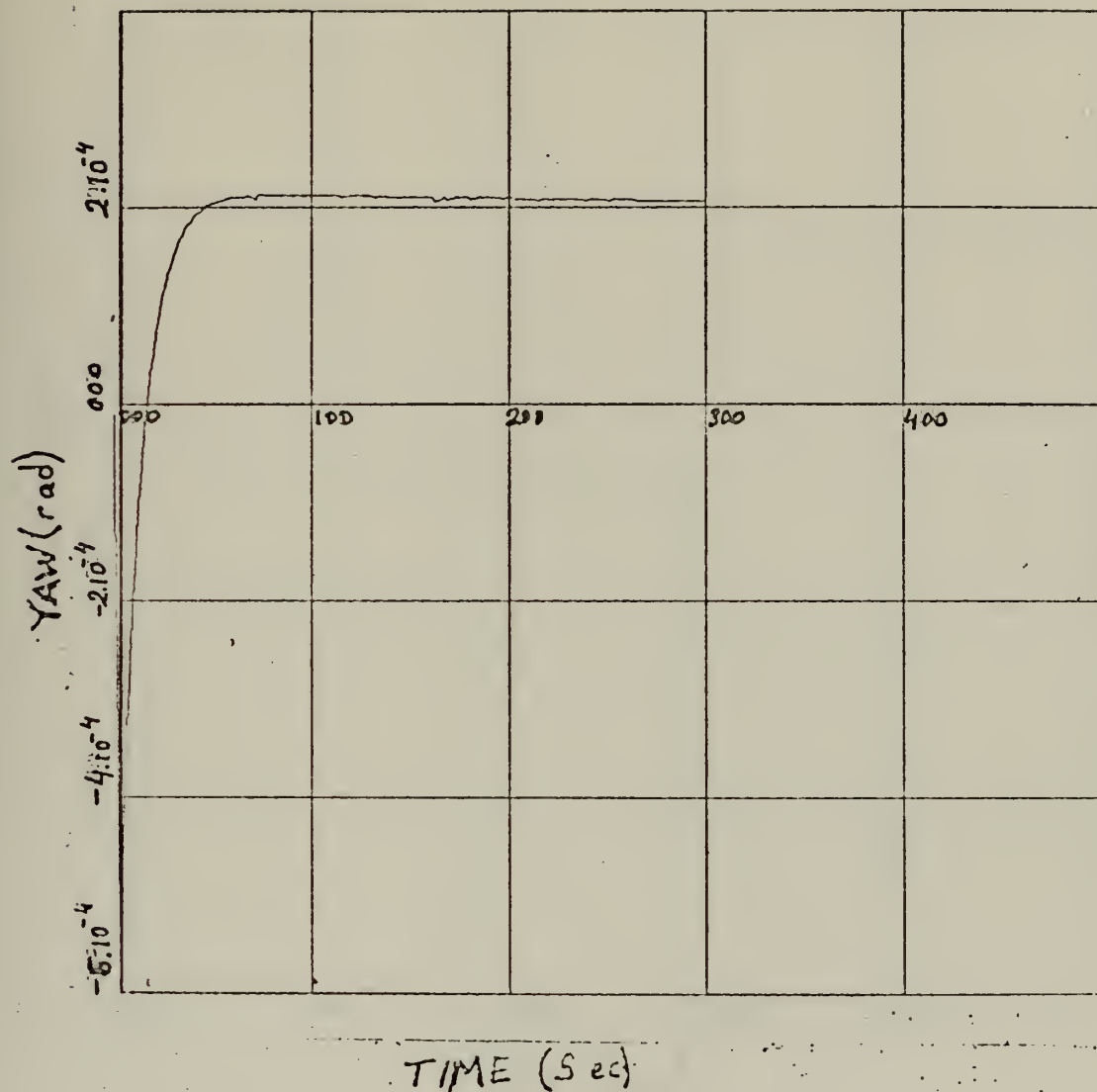


Figure 11. Variation of Yaw Versus Time for Wind Direction 090° , Velocity 3 miles/hr.

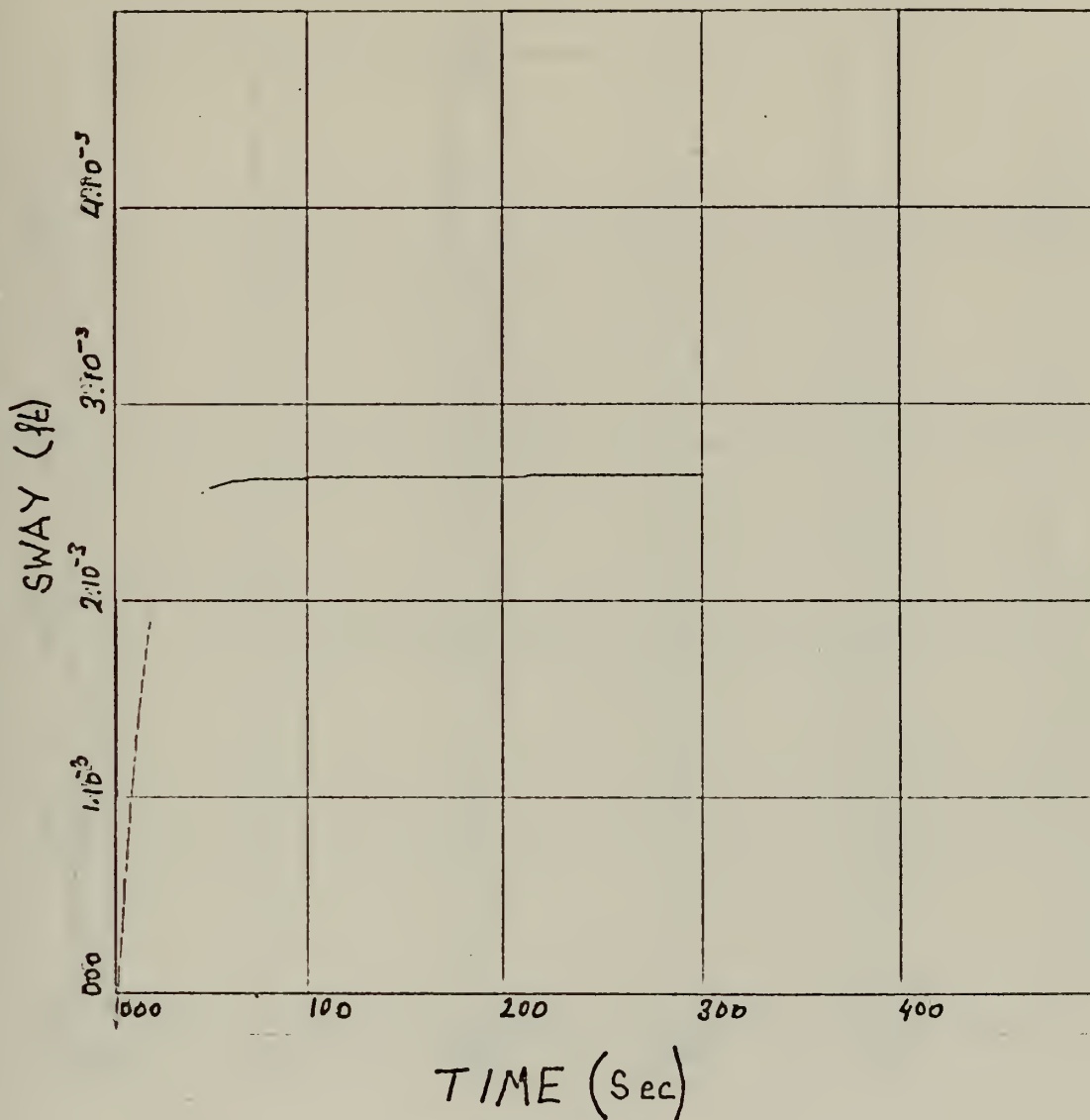


Figure 12. Variation of Sway Versus Time for Wind Direction 090°, Velocity 3 miles/hr.

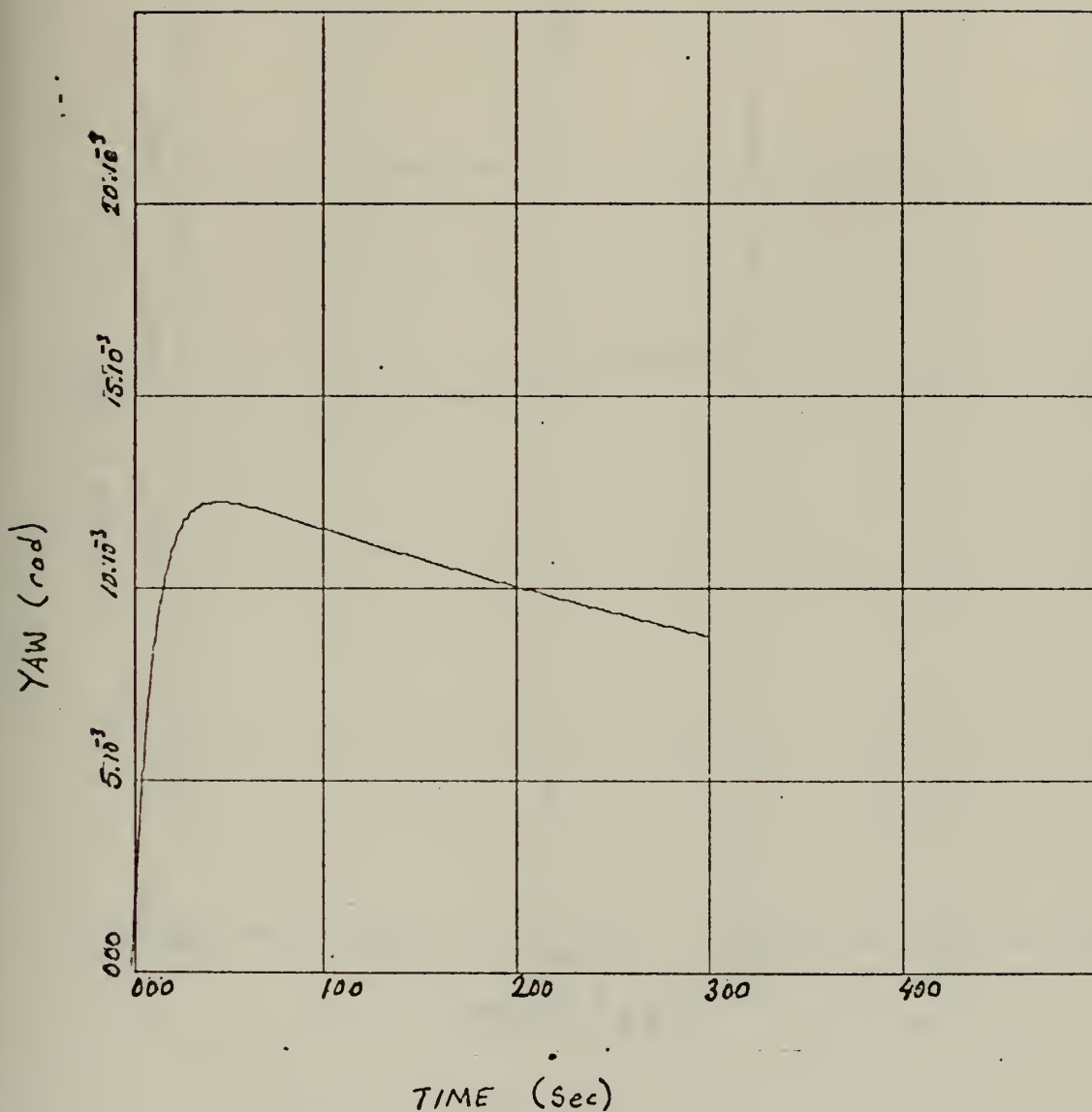


Figure 13. Variation of Yaw Versus Time for Wind Direction 090°, Velocity 5 miles/hr.

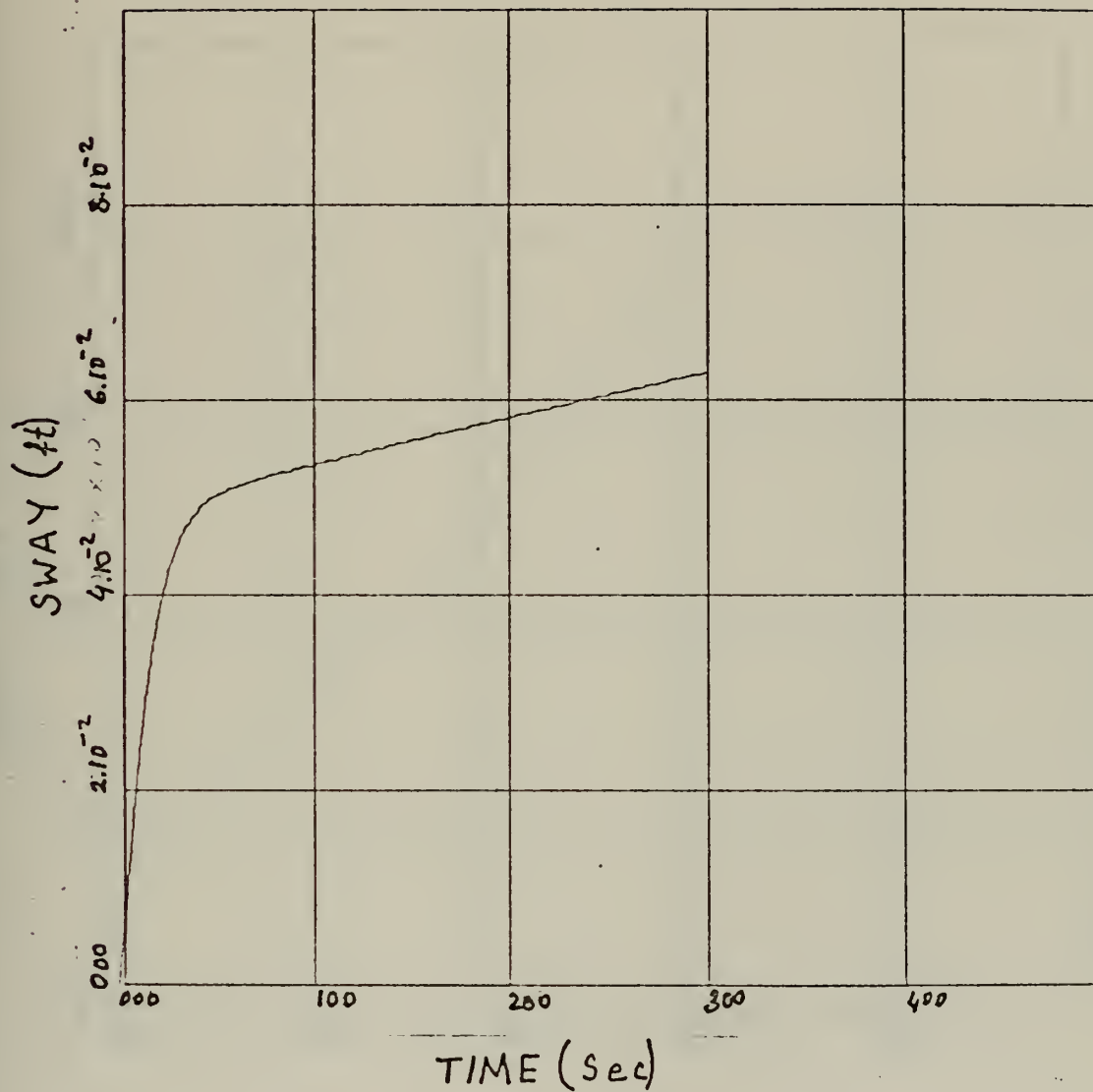


Figure 14. Variation of Sway Versus Time for Wind Direction 090° , Velocity 5 miles/hr.

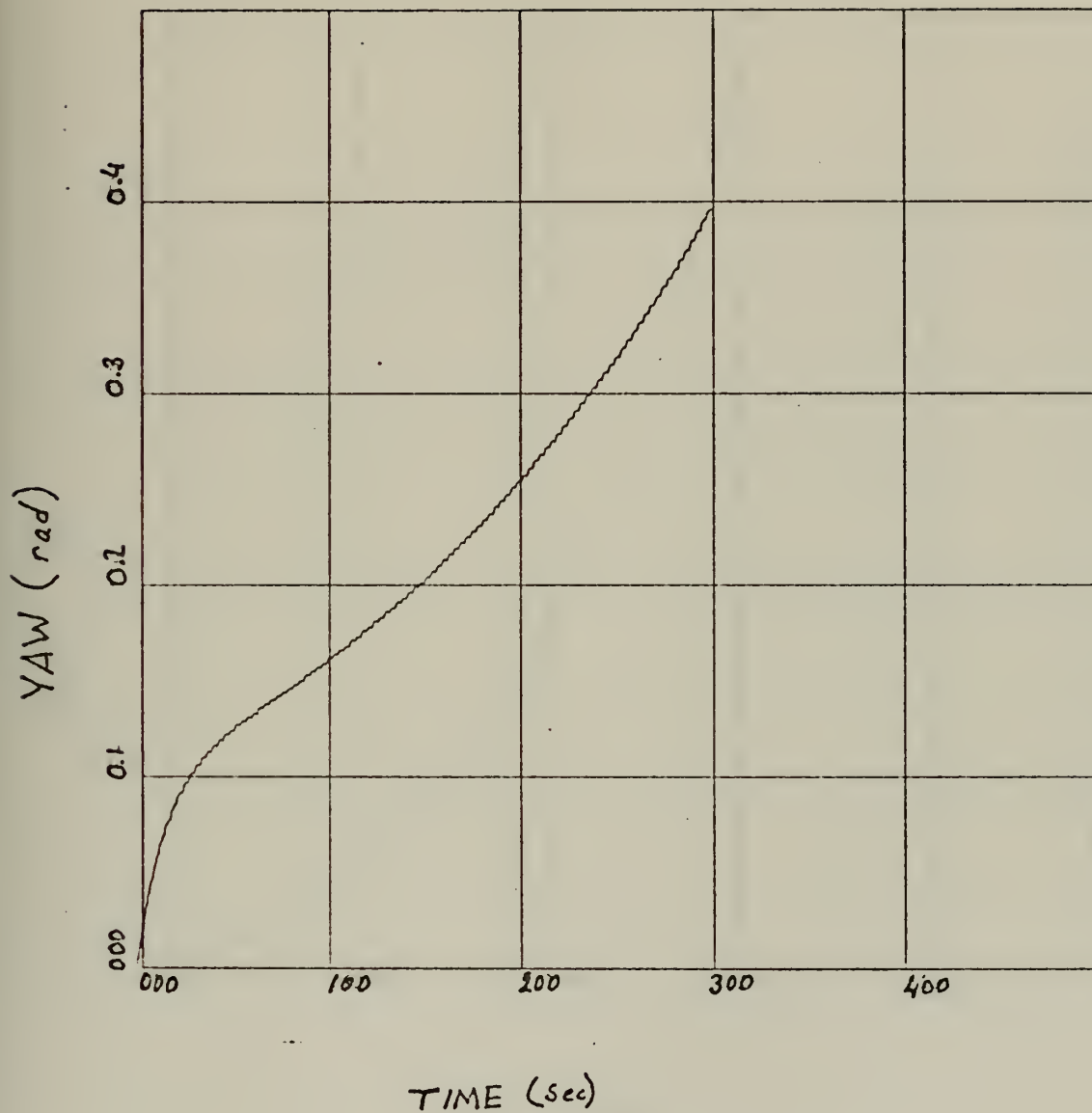


Figure 15. Variation of Yaw Versus Time for Wind Direction 090°, Velocity 7 miles/hr.

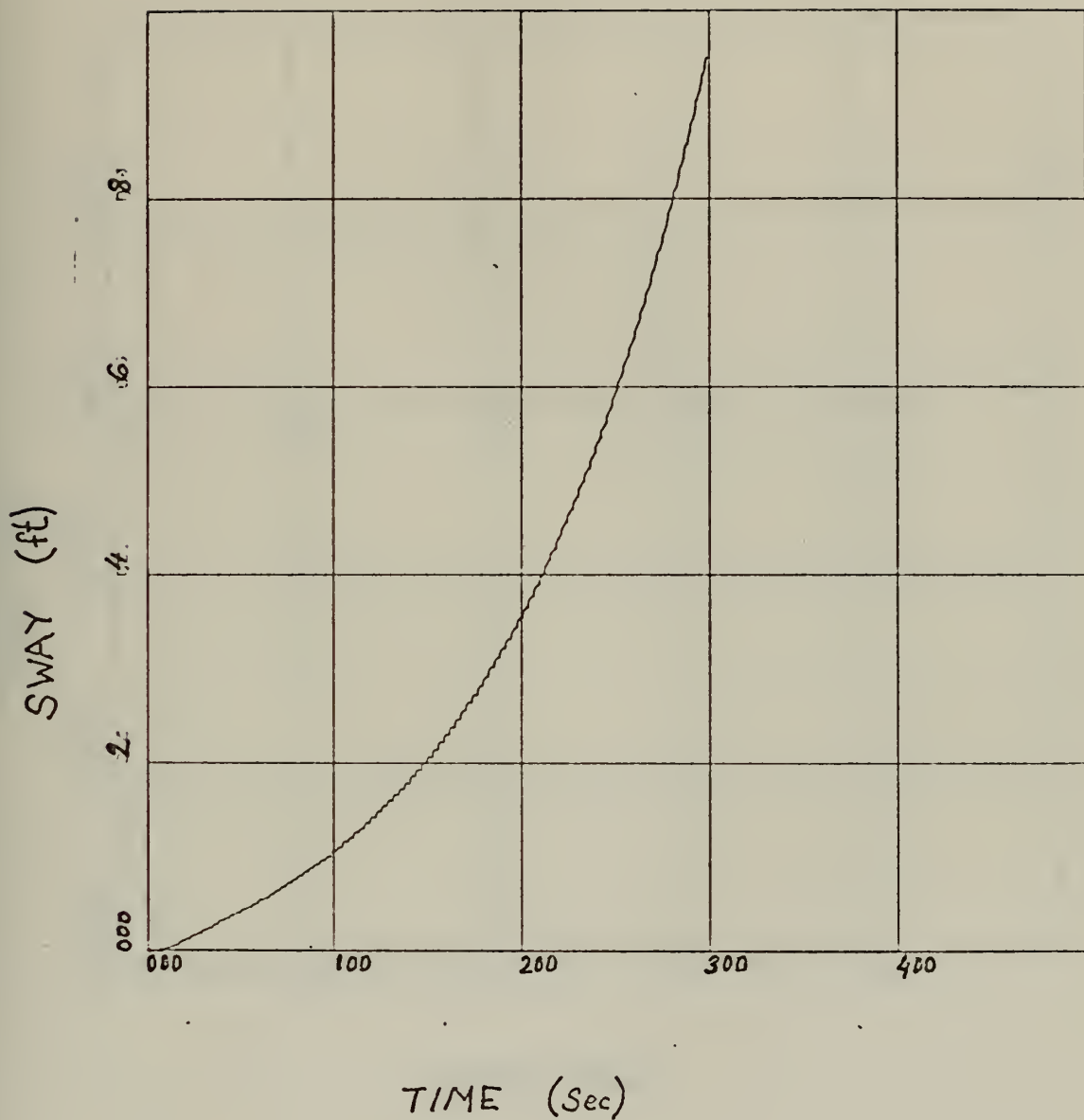


Figure 16. Variation of Sway Versus Time for Wind Direction 090°, Velocity 7 miles/hr.

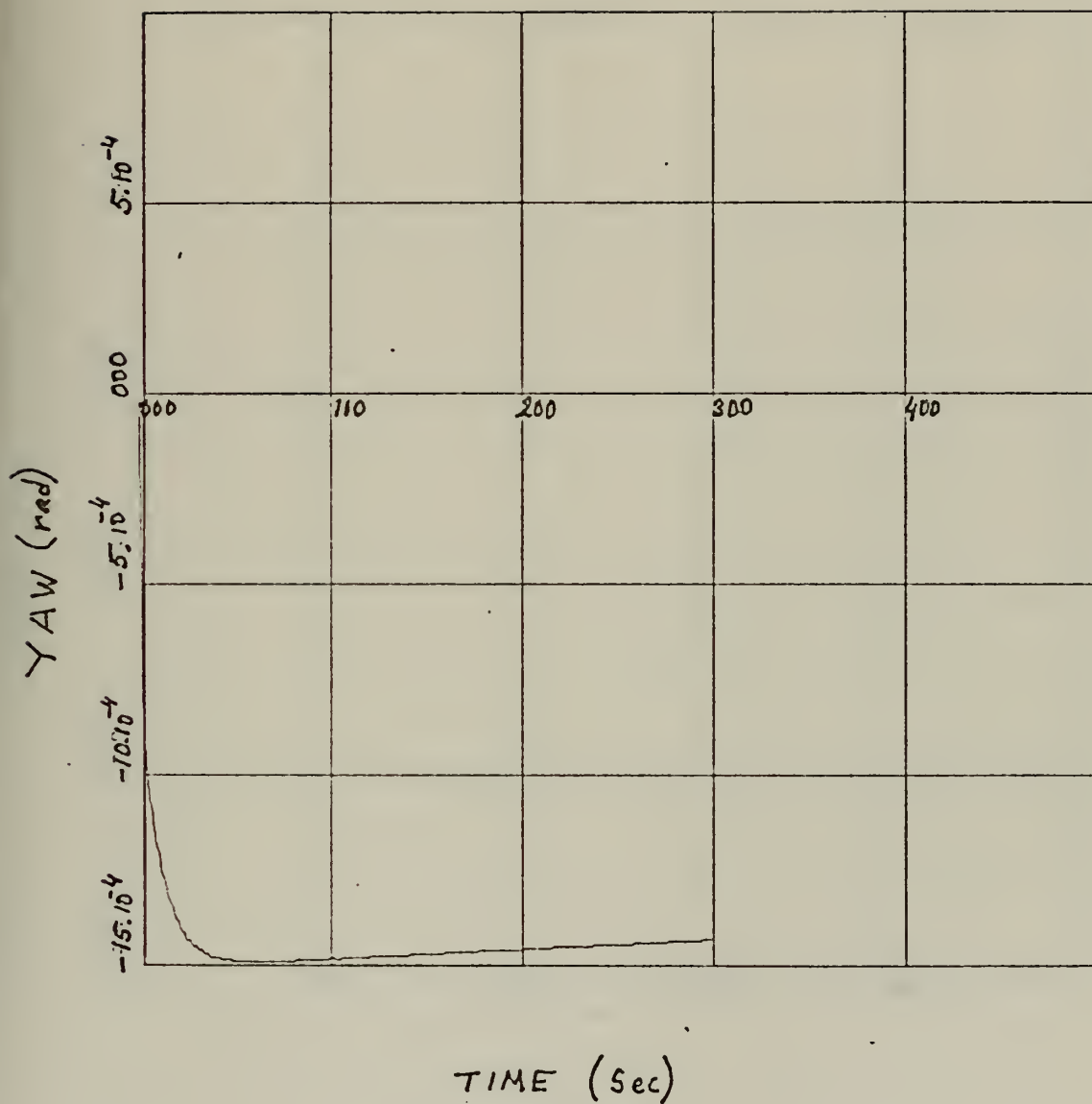


Figure 17. Variation of Yaw Versus Time for Wind Direction 180°, Velocity 1 mile/hr.

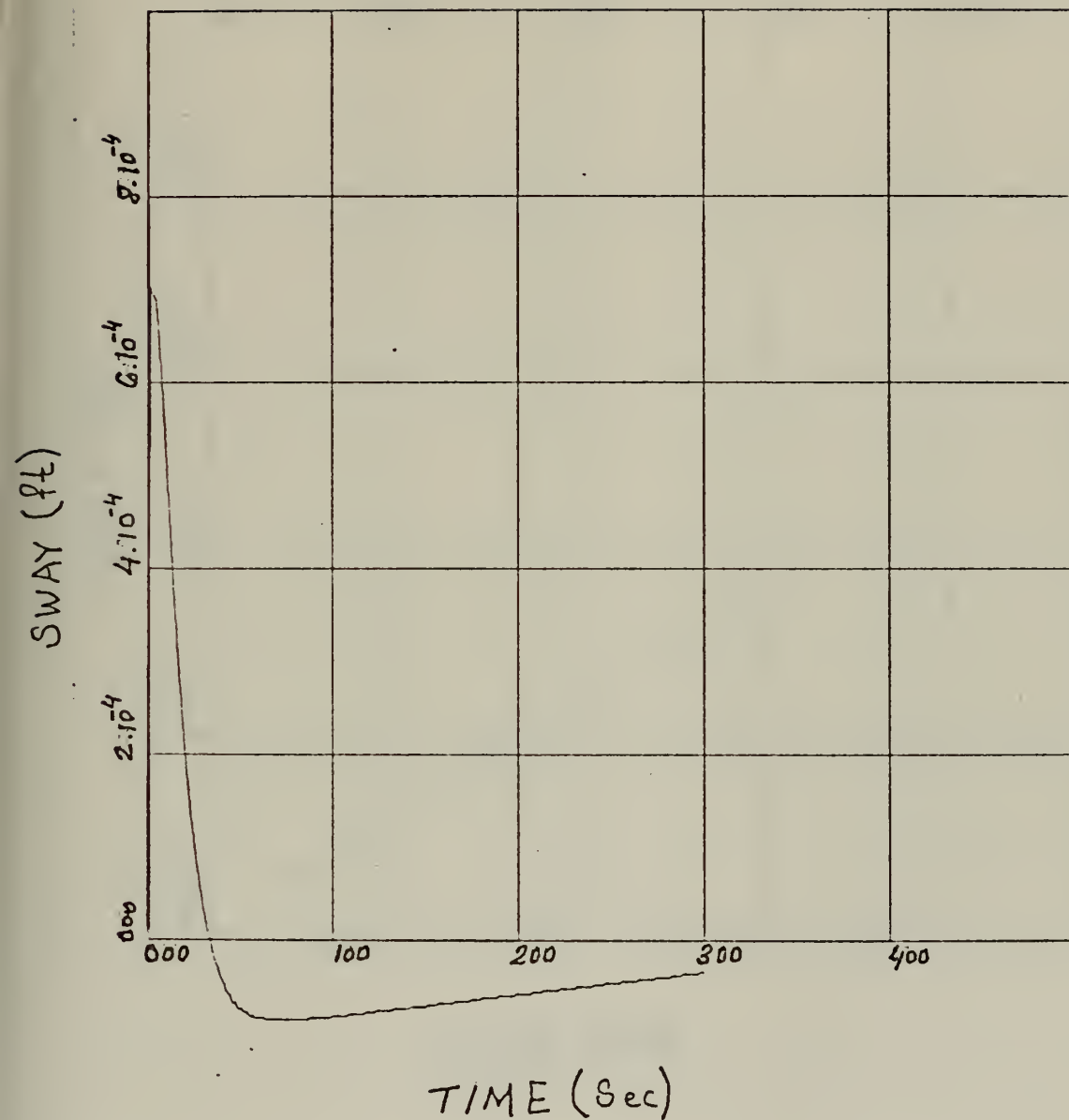


Figure 18. Variation of Sway Versus Time for Wind Direction 180°, Velocity 1 mile/hr.

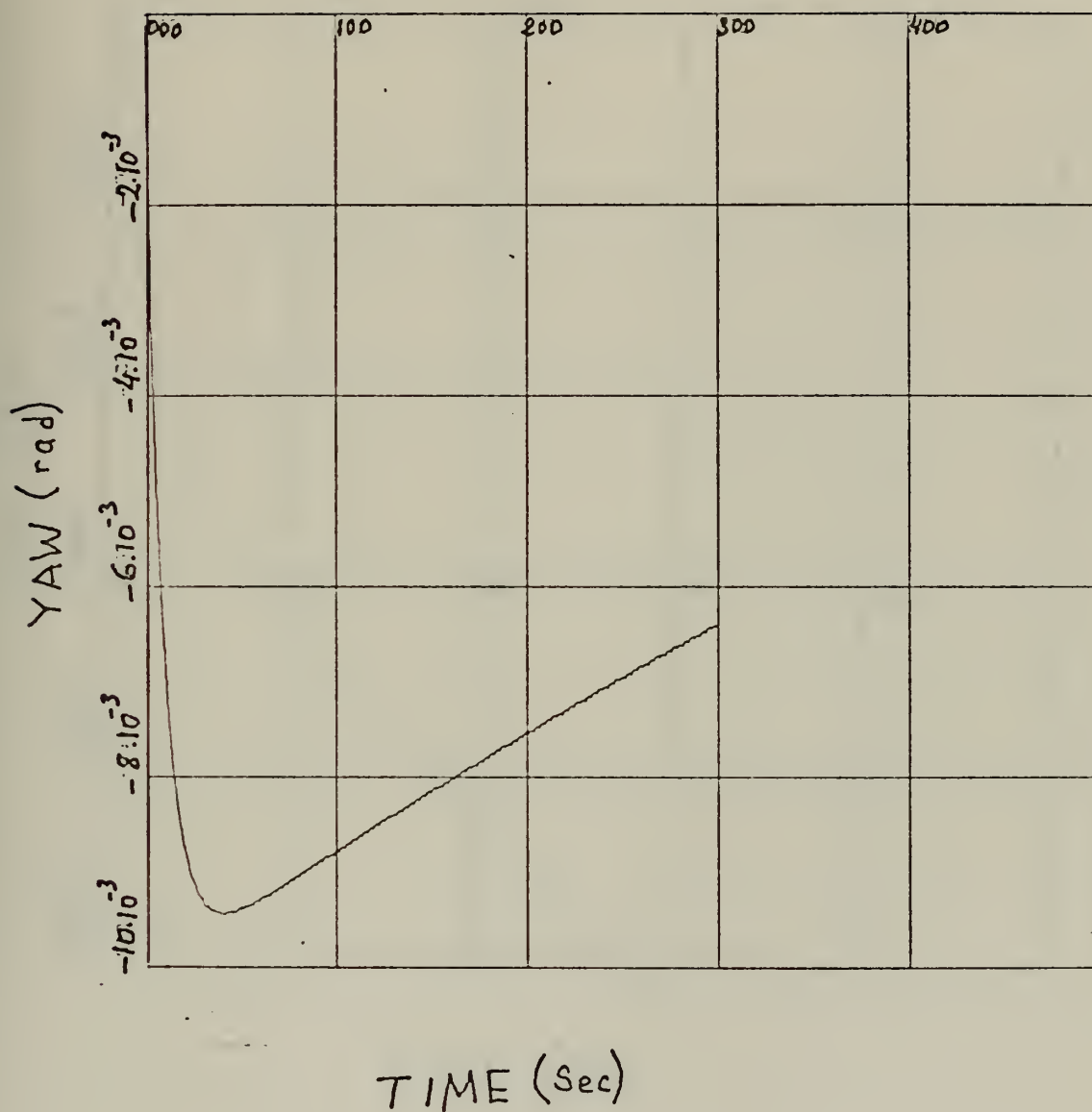


Figure 19. Variation of Yaw Versus Time for Wind Direction 180° , Velocity 3 miles/hr.

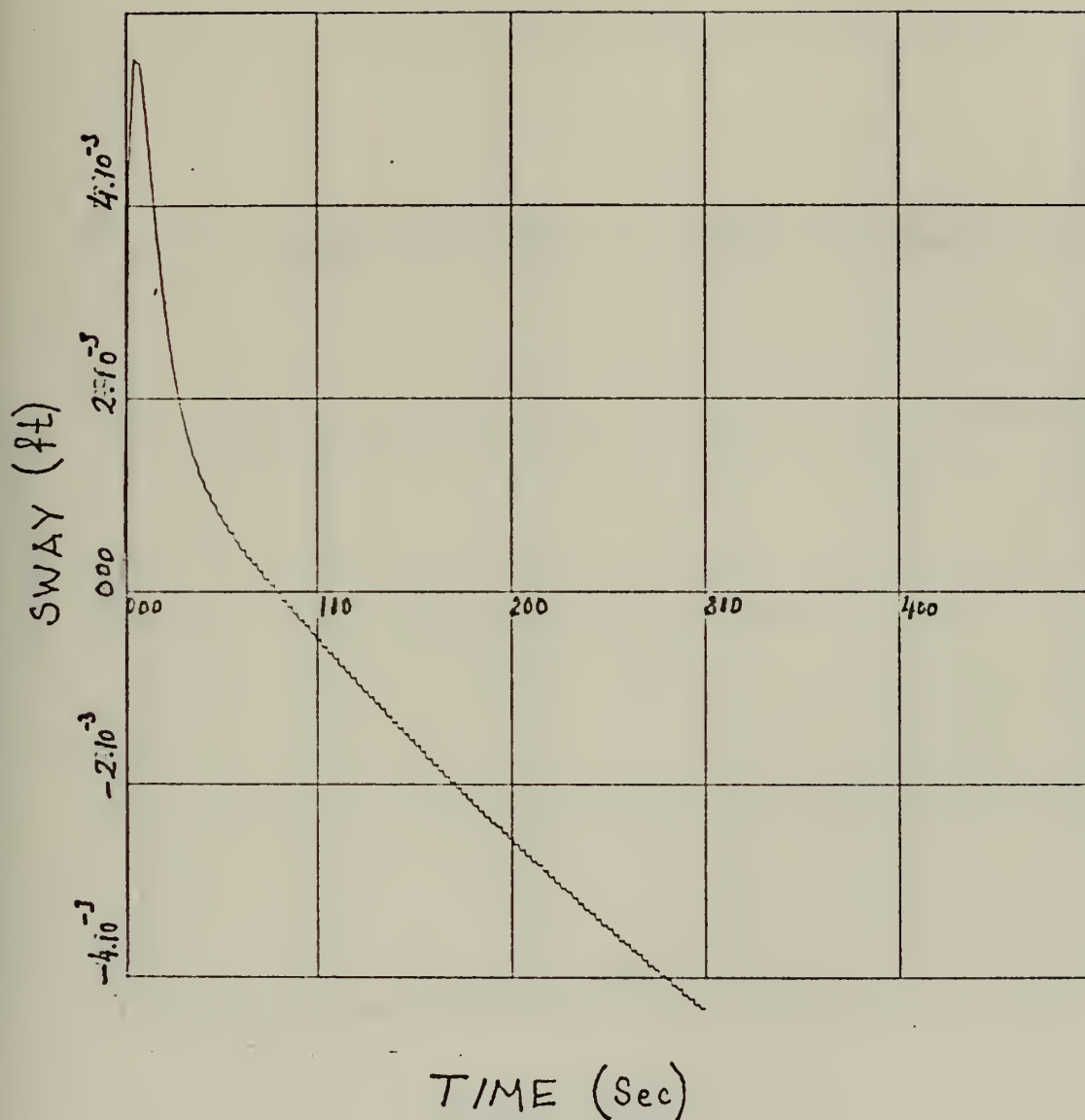


Figure 20. Variation of Sway Versus Time for Wind Direction 180° , Velocity 3 miles/hr.

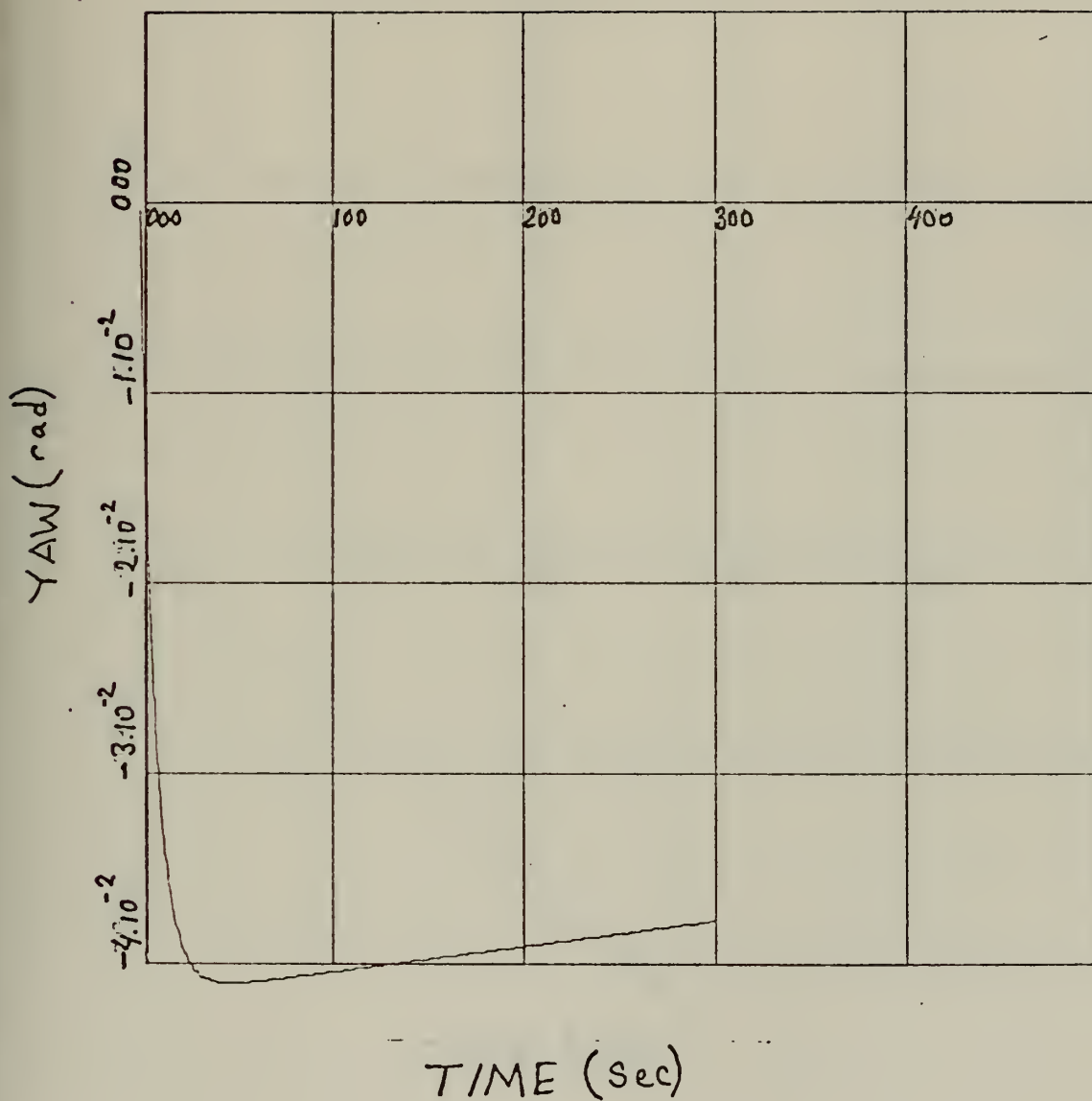


Figure 21. Variation of Yaw Versus Time for Wind Direction 180°, Velocity 5 miles/hr.

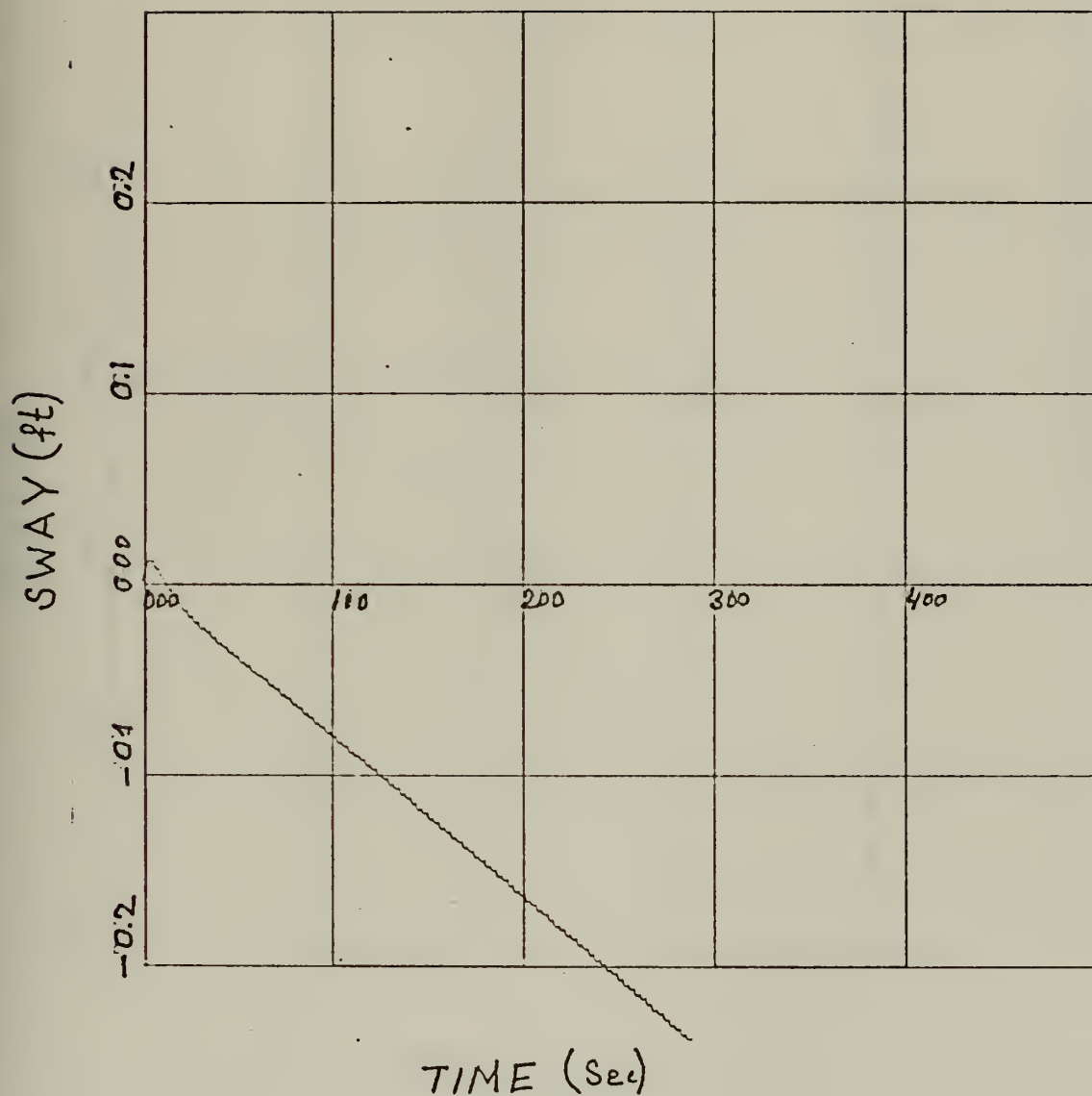


Figure 22. Variation of Sway Versus Time for Wind Direction 180°, Velocity 5 miles/hr.

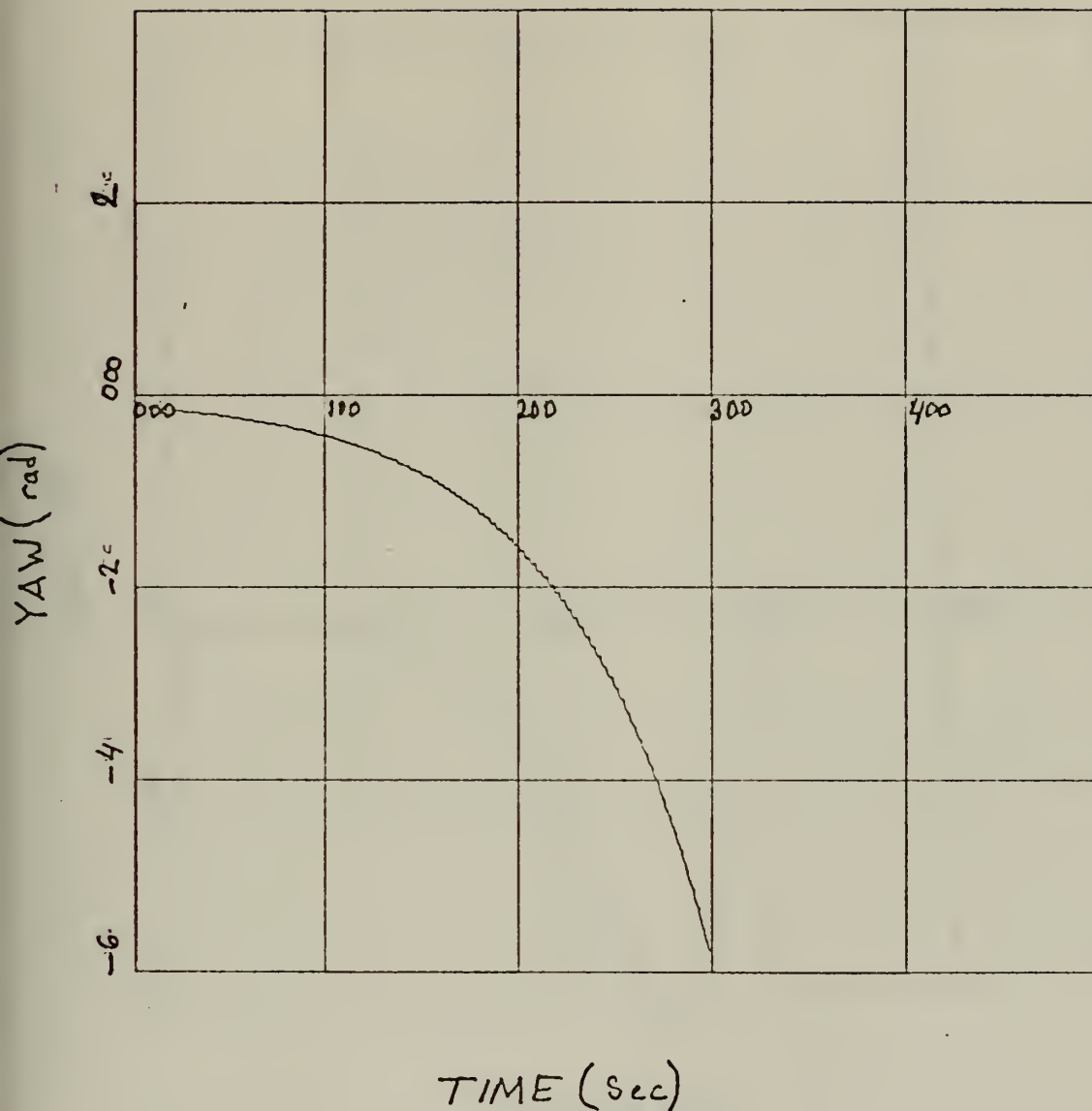


Figure 23. Variation of Yaw Versus Time for Wind Direction 180°, Velocity 7 miles/hr.

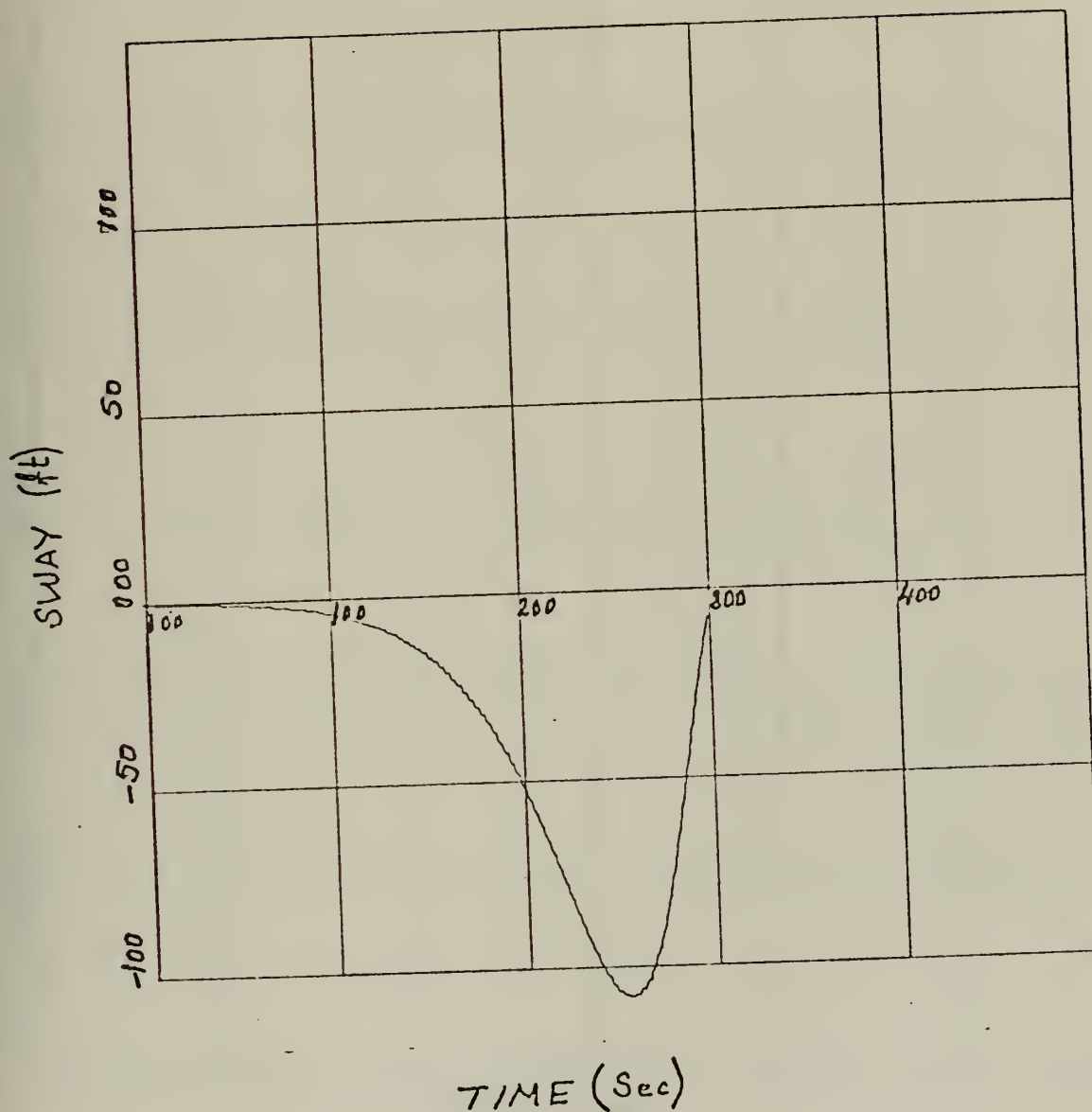


Figure 24. Variation of Sway Versus Time for Wind Direction 180°, Velocity 7 miles/hr.

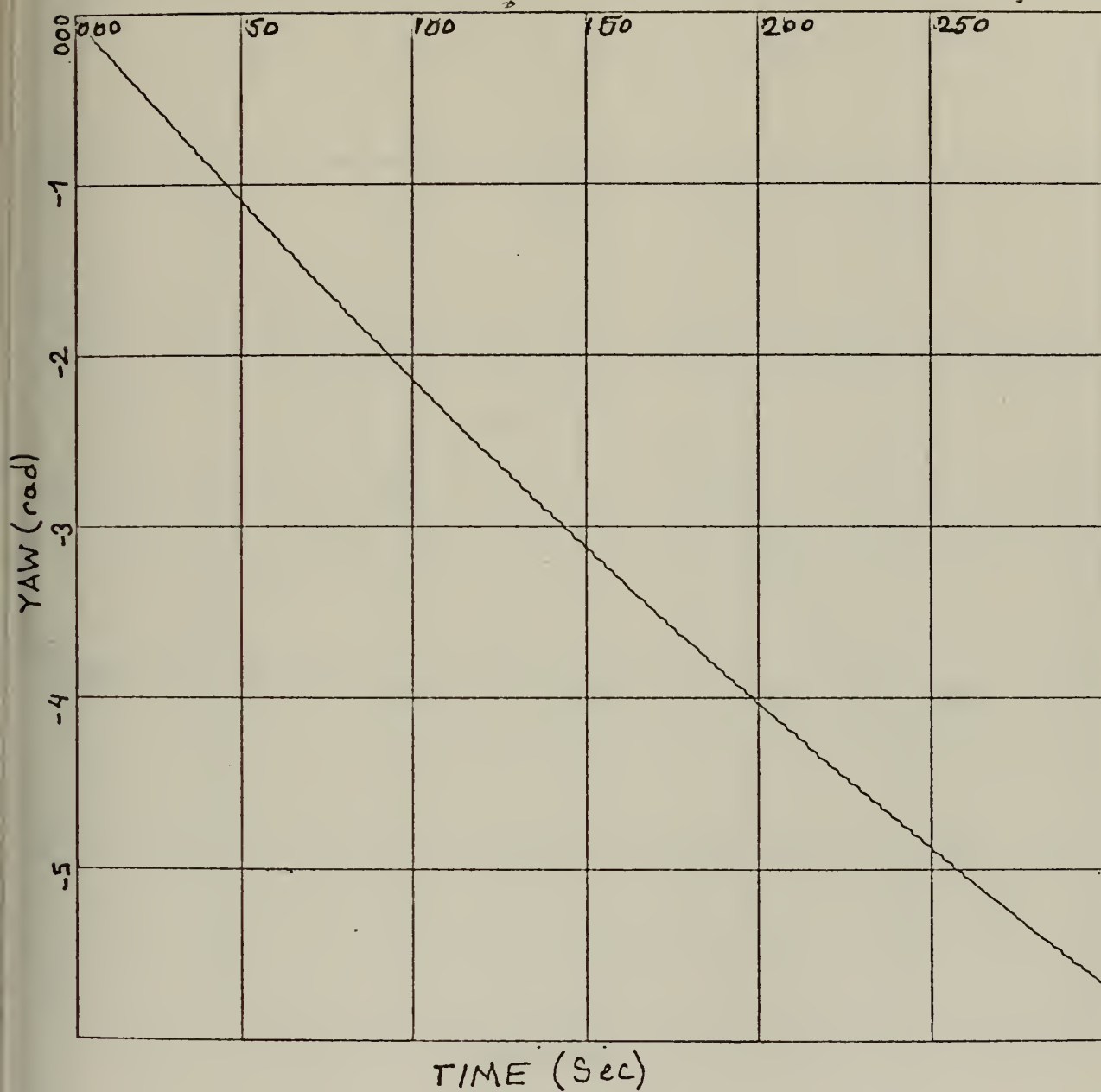


Figure 25. Variation of Yaw Versus Time for Wind Direction 090°, Velocity 5 miles/hr, Rudder Deflection 15°.

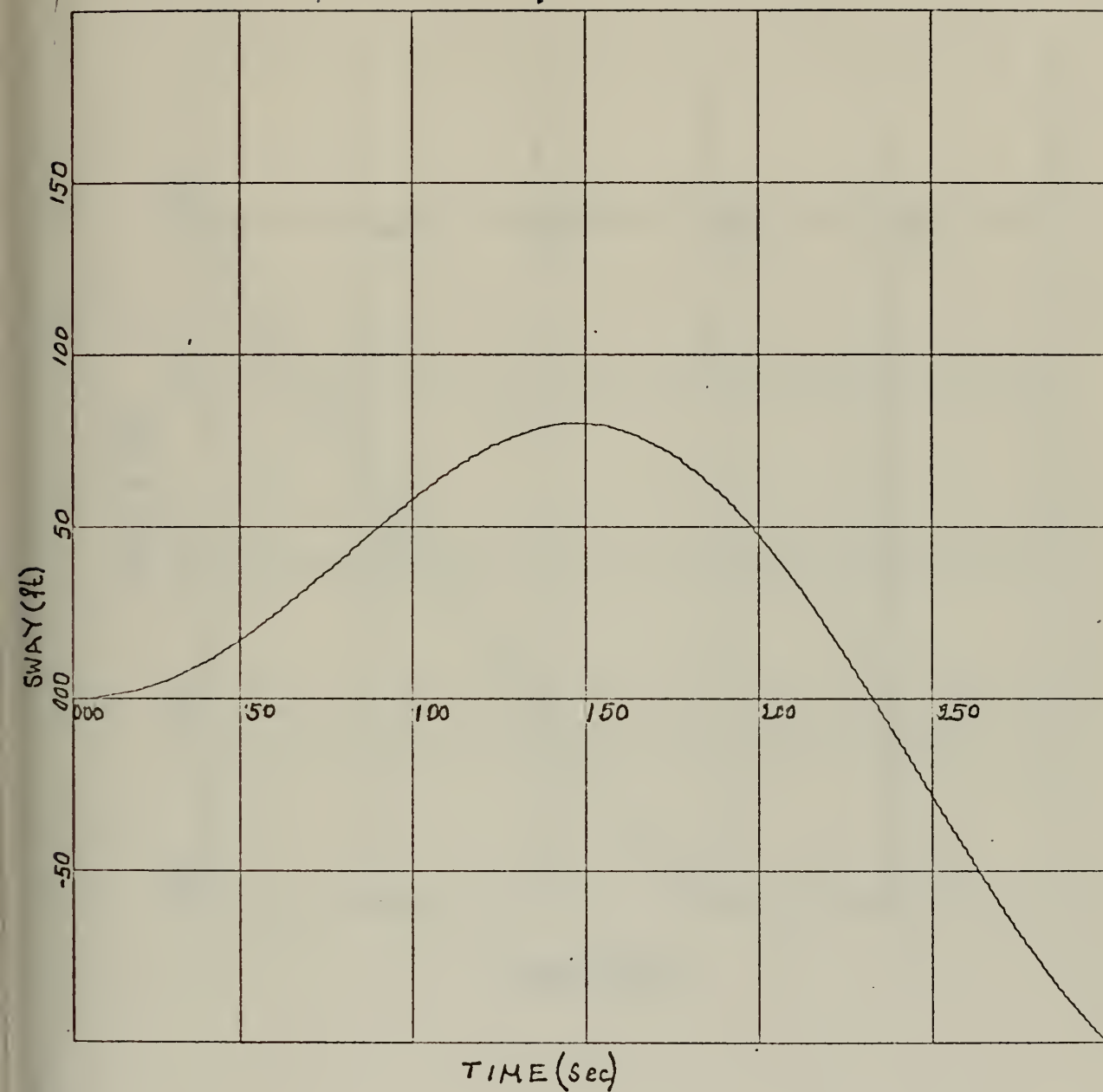


Figure 26. Variation of Sway Versus Time for Wind Direction 090° , Velocity 5 miles/hr, Rudder Deflection 15° .

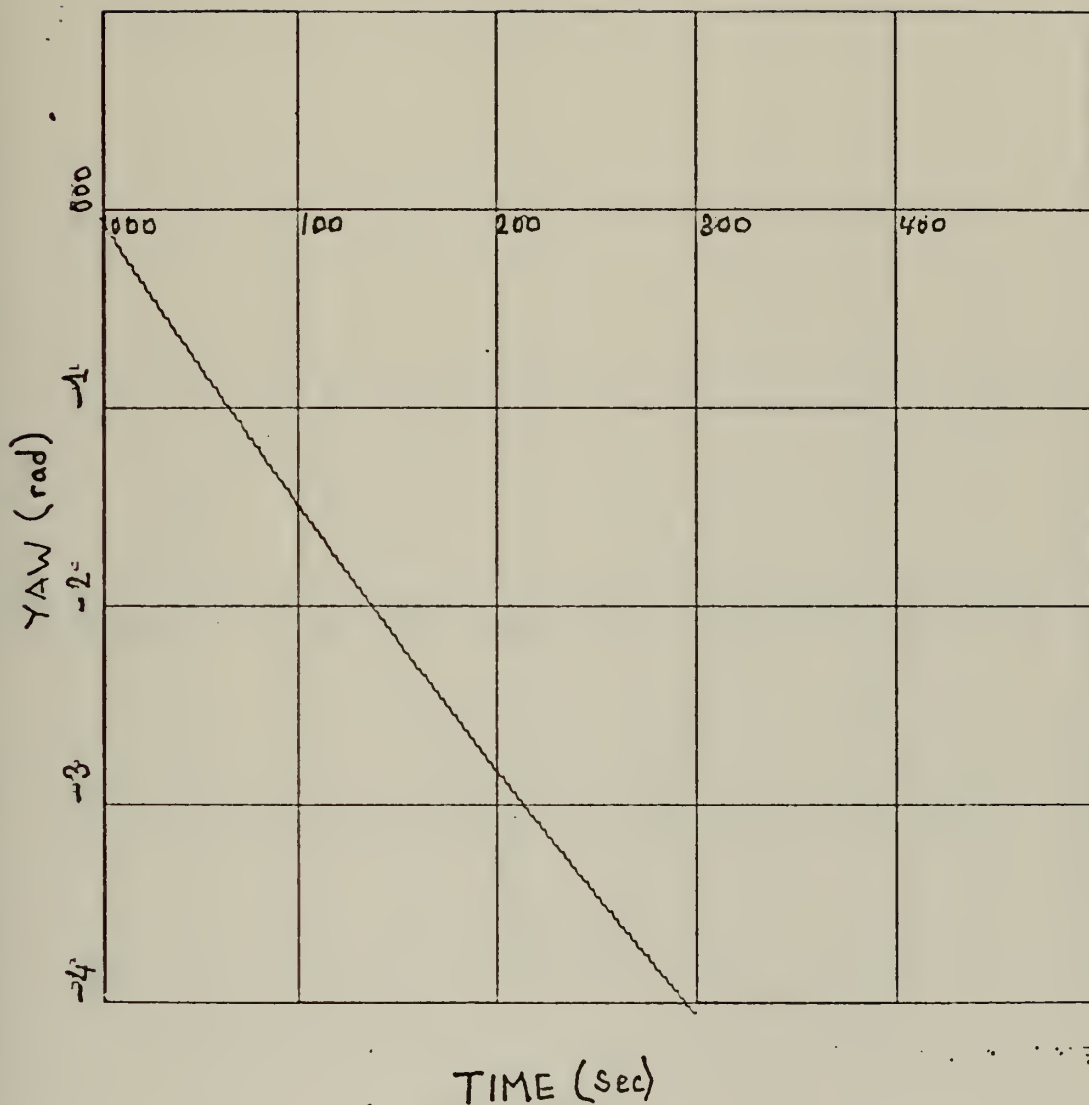


Figure 27. Variation of Yaw Versus Time for Wind Direction 180°, Velocity 3 miles/hr, Rudder Deflection 15°.

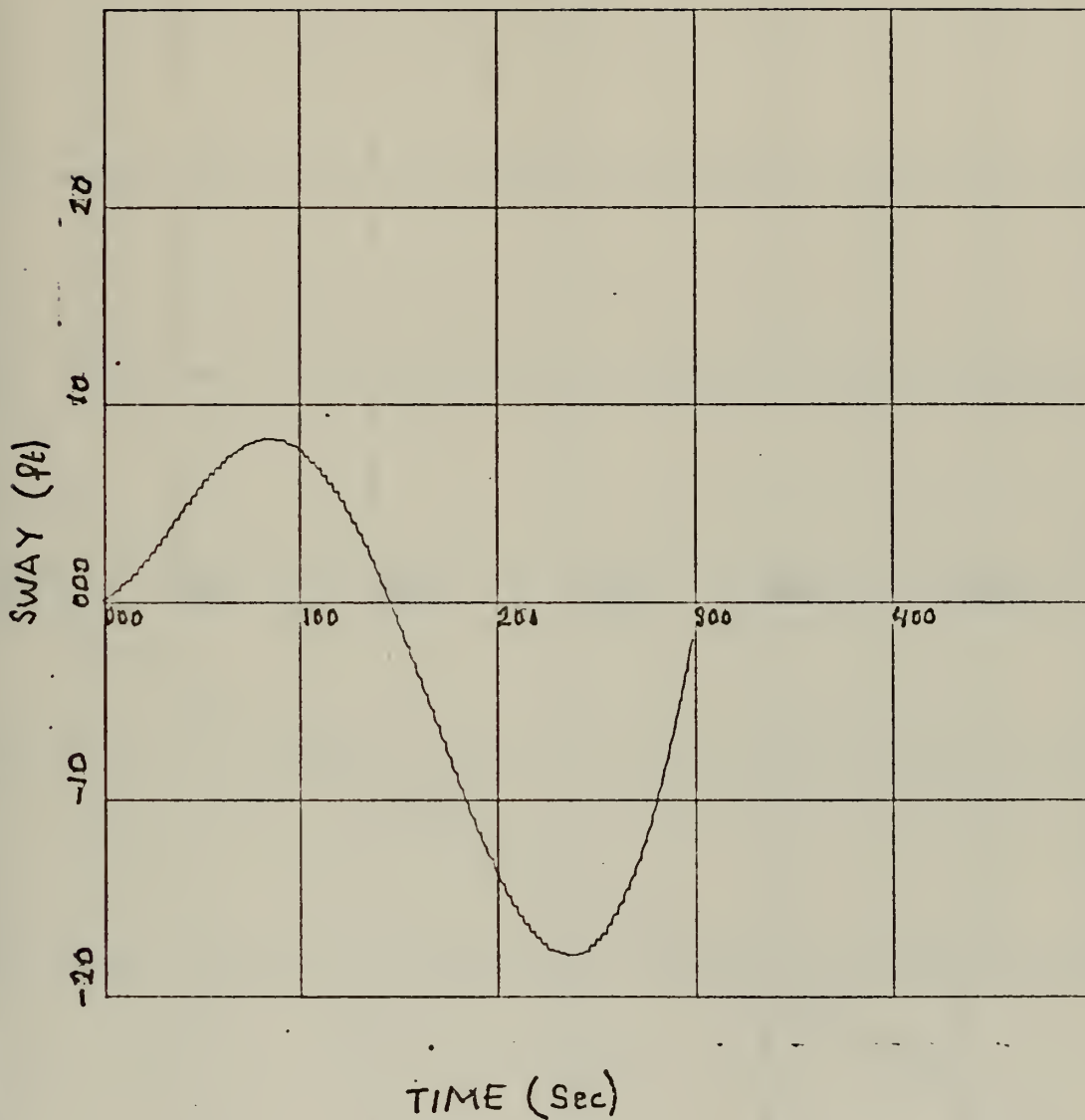


Figure 28. Variation of Sway Versus Time for Wind Direction 180°, Velocity 3 miles/hr, Rudder Deflection 15°.

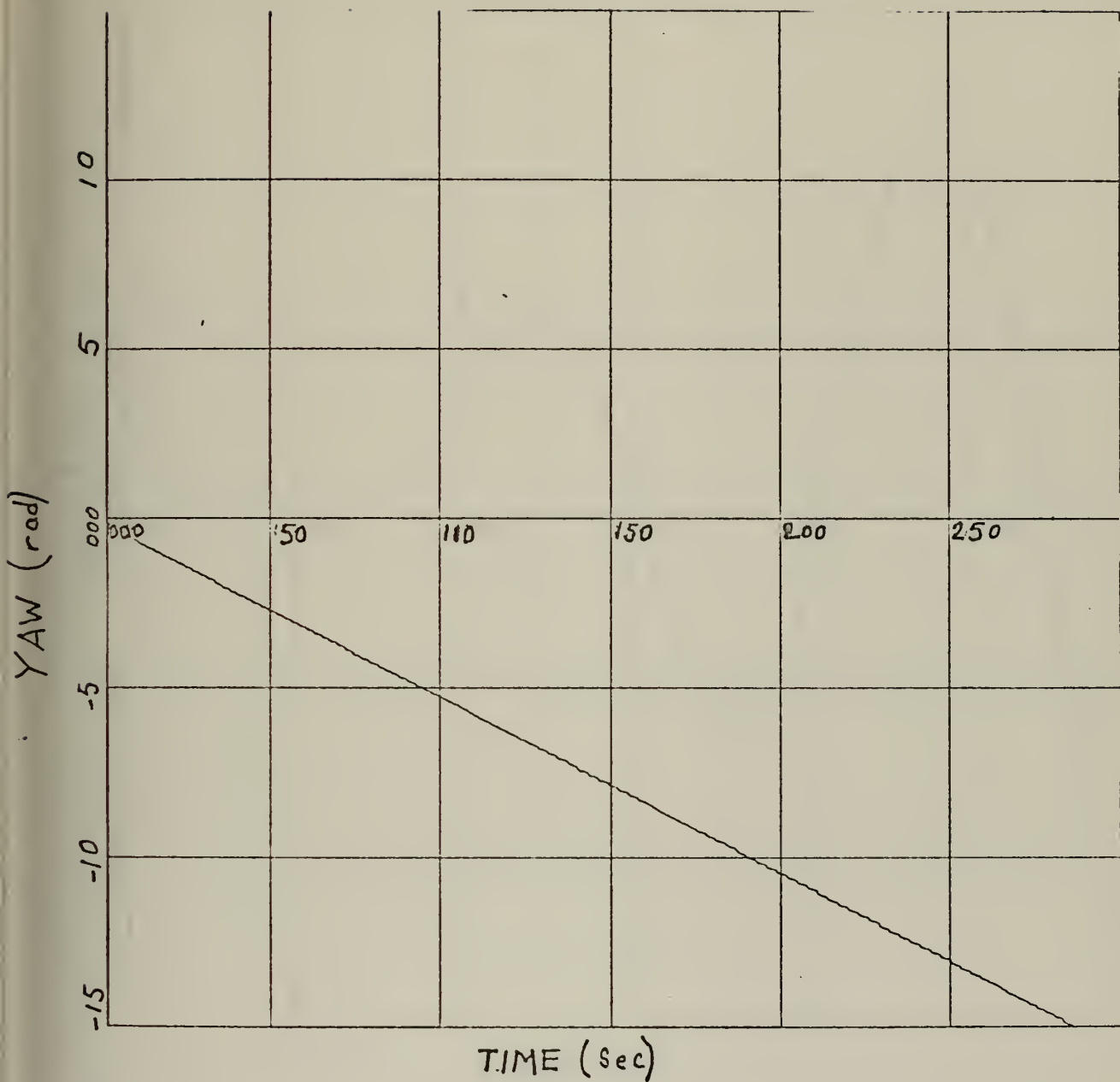


Figure 29. Variation of Yaw Versus Time for Wind Direction 180°, Velocity 5 miles/hr, Rudder Deflection 15°.

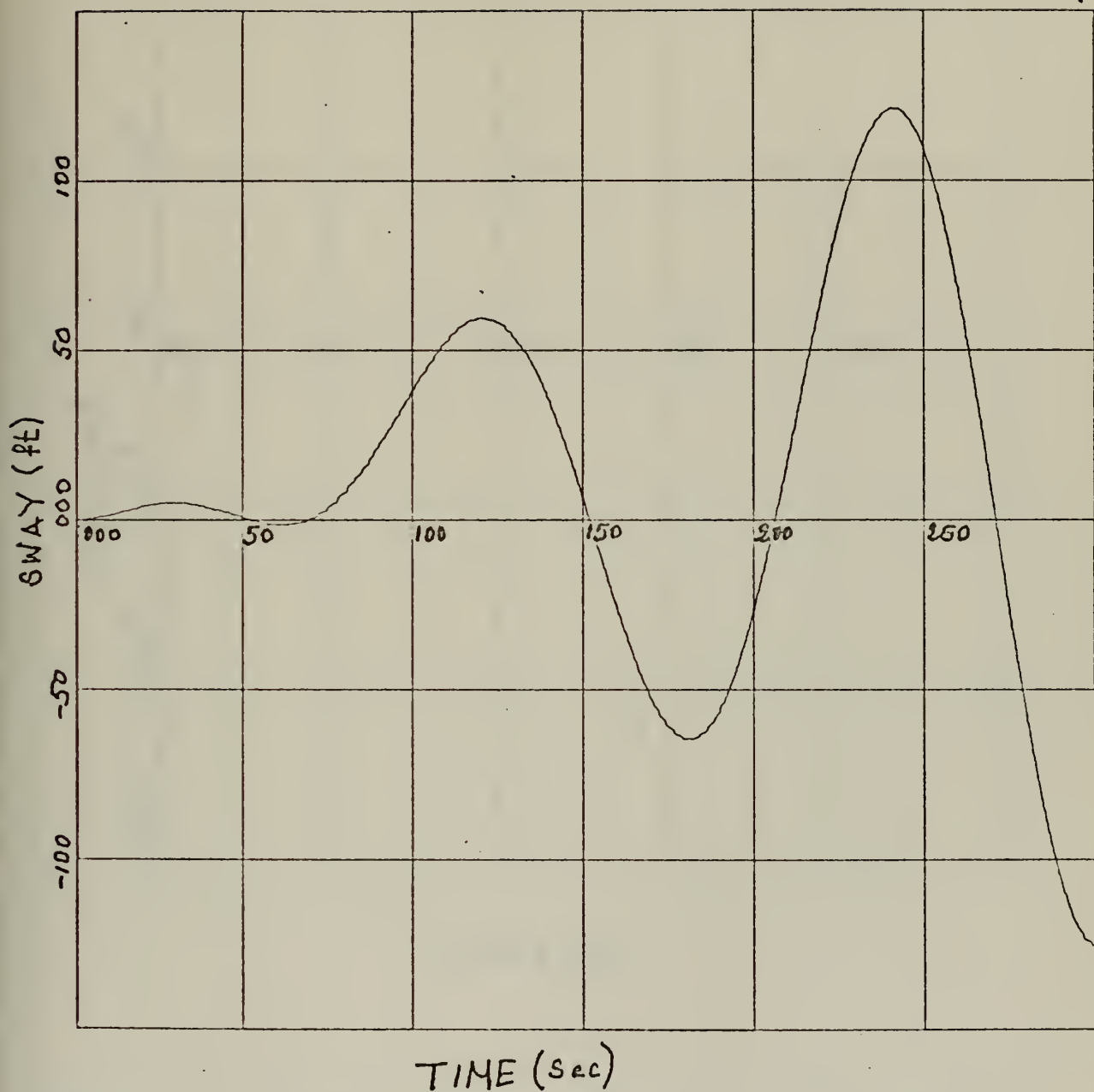


Figure 30. Variation of Sway Versus Time for Wind Direction 180° , Velocity 5 miles/hr, Rudder Deflection 15° .

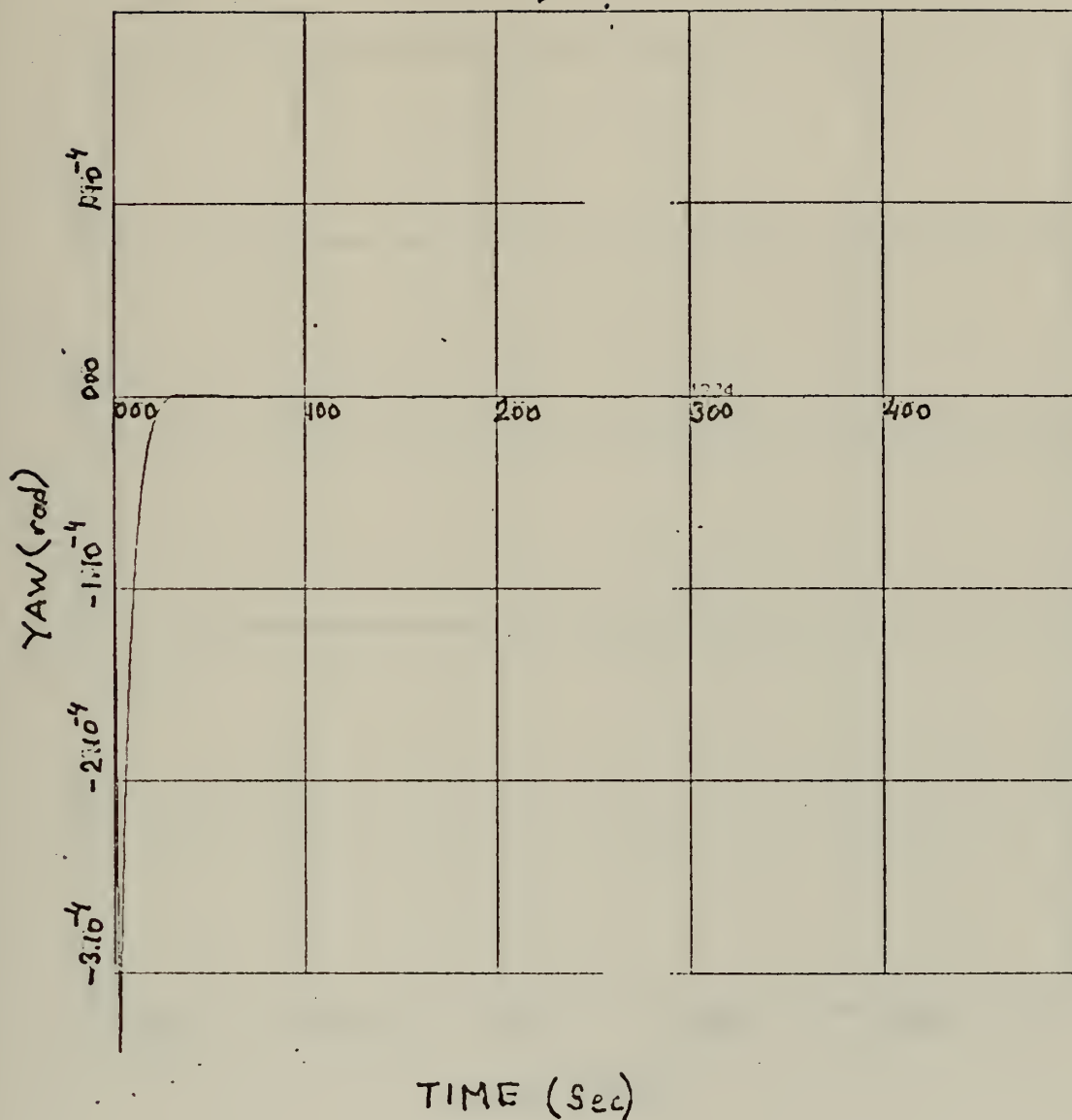


Figure 31. Variation of Yaw Versus Time for Wind Direction 000° , Velocity 1 mile/hr, Automatically Steered.

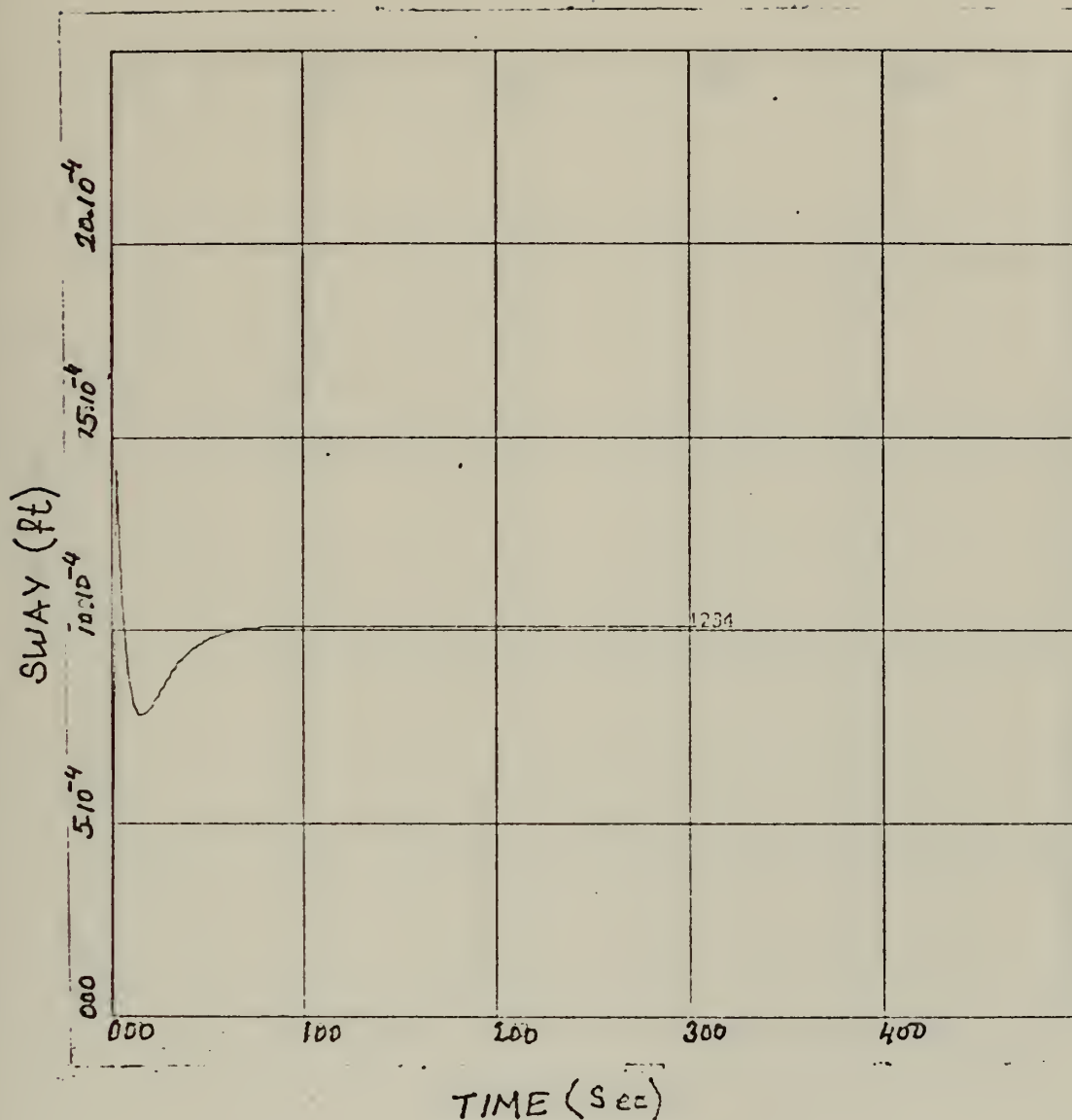


Figure 32. Variation of Sway Versus Time for Wind Direction 000° , Velocity 1 mile/hr, Automatically Steered.

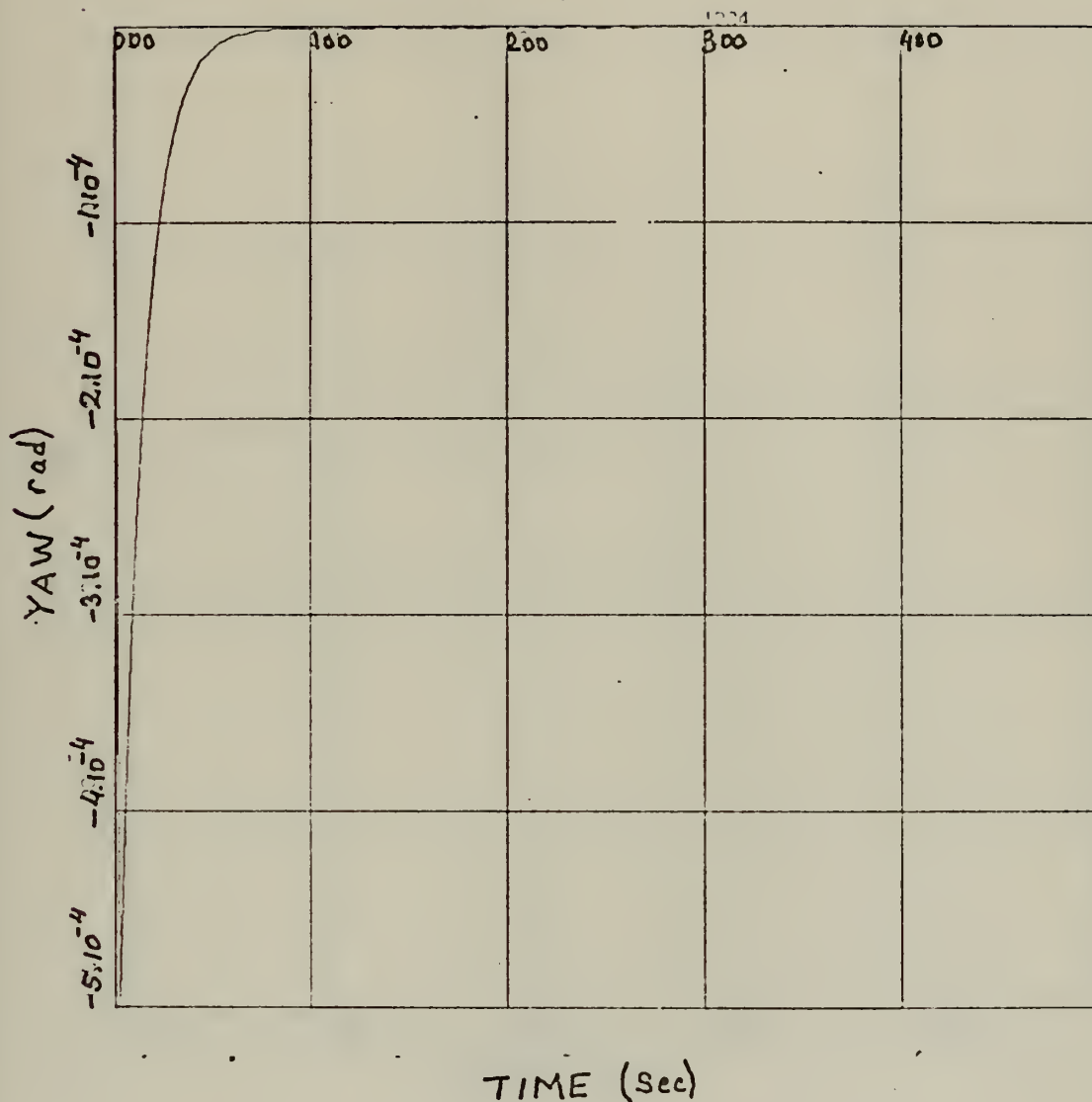


Figure 33. Variation of Yaw Versus Time for Wind Direction 000°, Velocity 3 miles/hr, Automatically Steered.

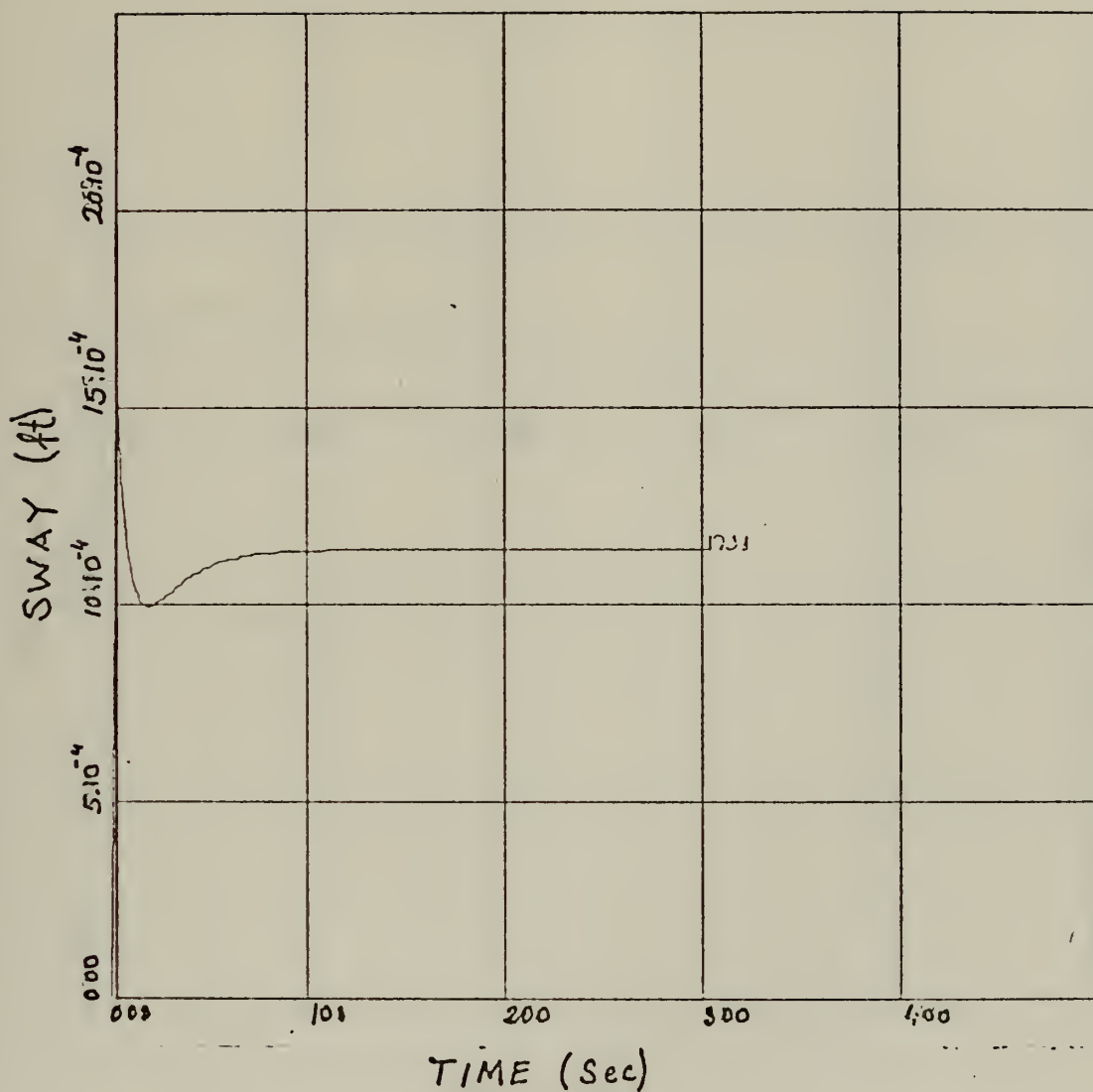


Figure 34. Variation of Sway Versus Time for Wind Direction 000°, Velocity 3 miles/hr, Automatically Steered.

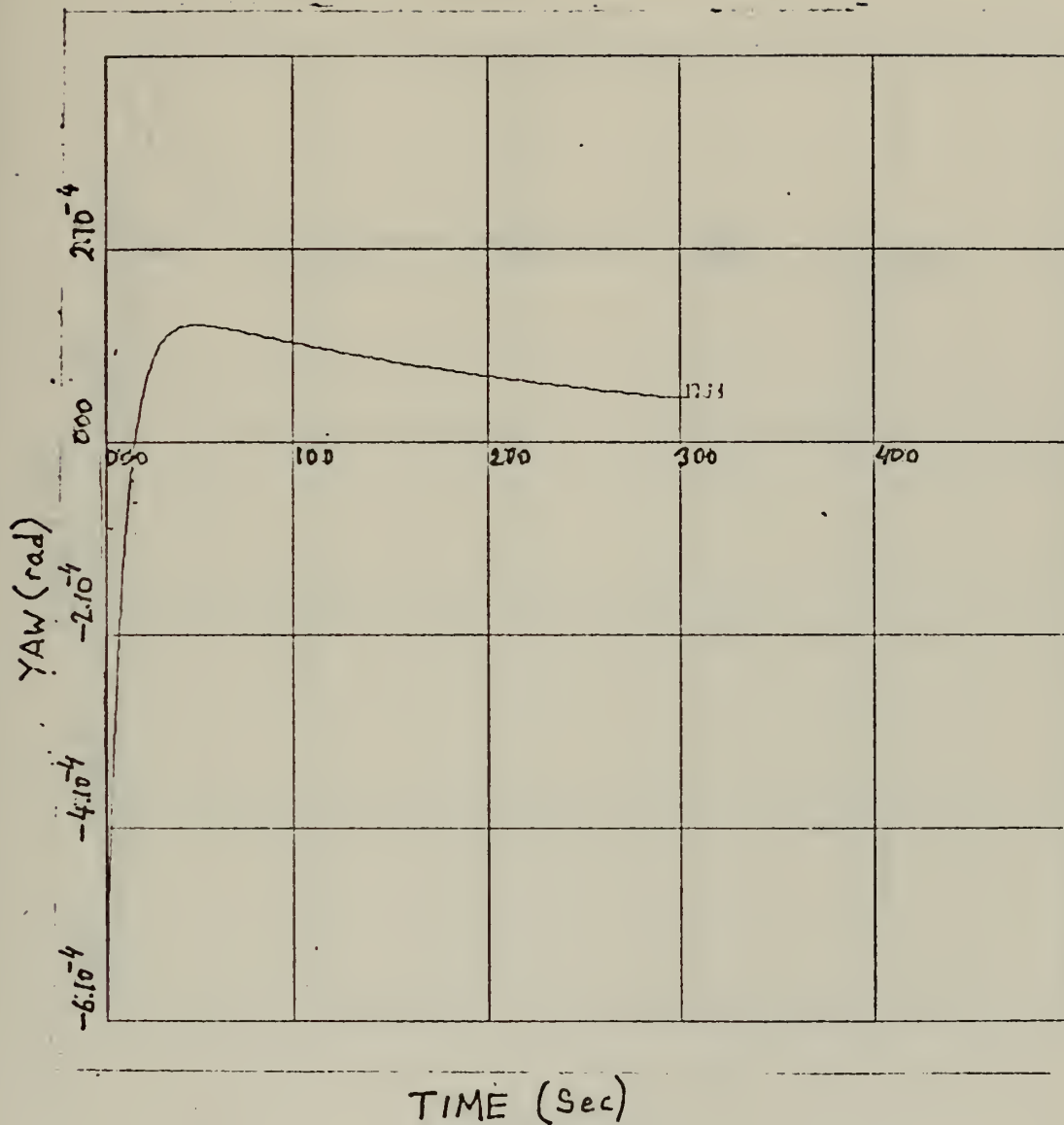


Figure 35. Variation of Yaw Versus Time for Wind Direction 000°, Velocity 5 miles/hr, Automatically Steered.

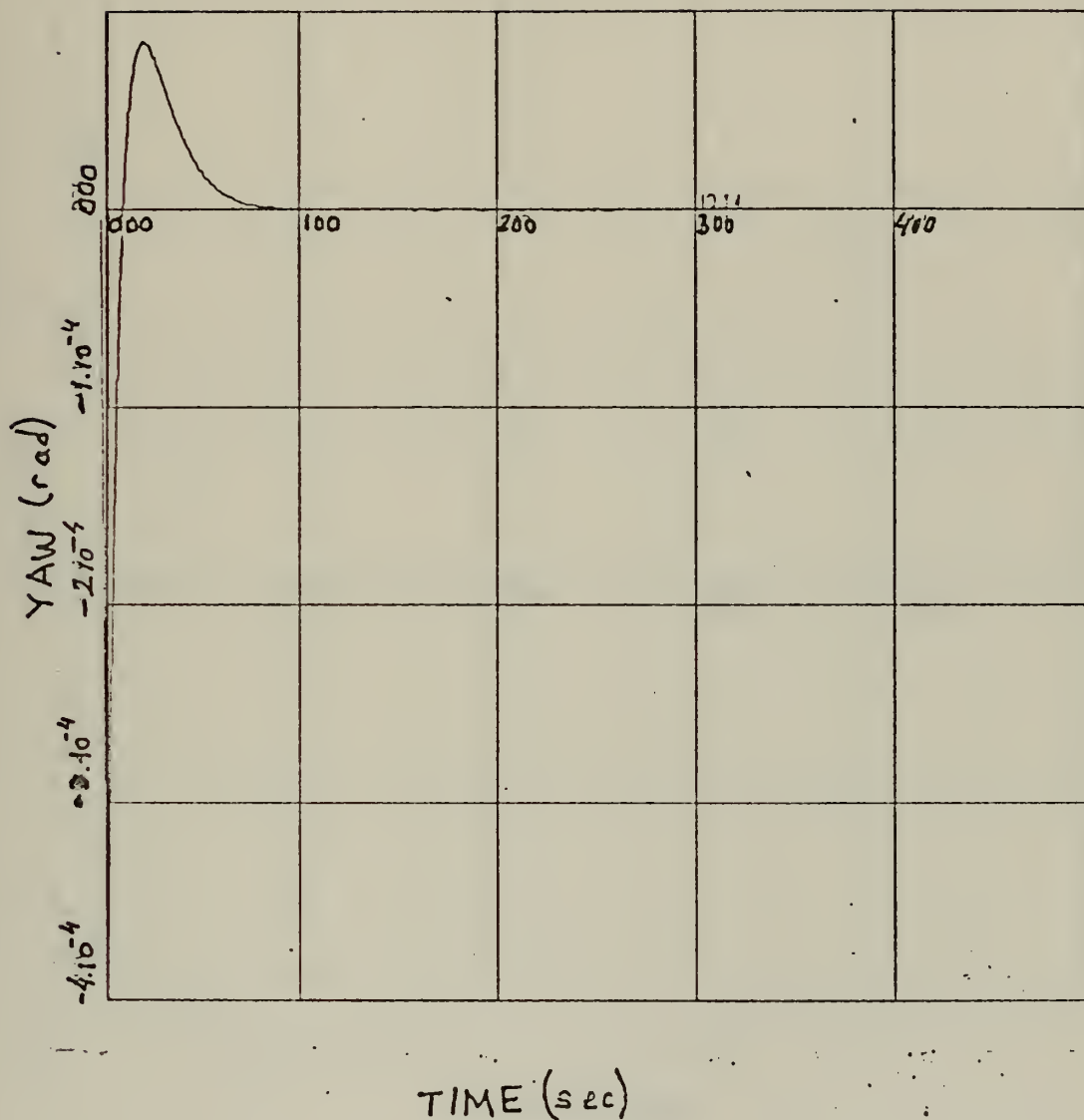


Figure 36. Variation of Yaw Versus Time for Wind Direction 090°, Velocity 3 miles/hr, Automatically Steered.

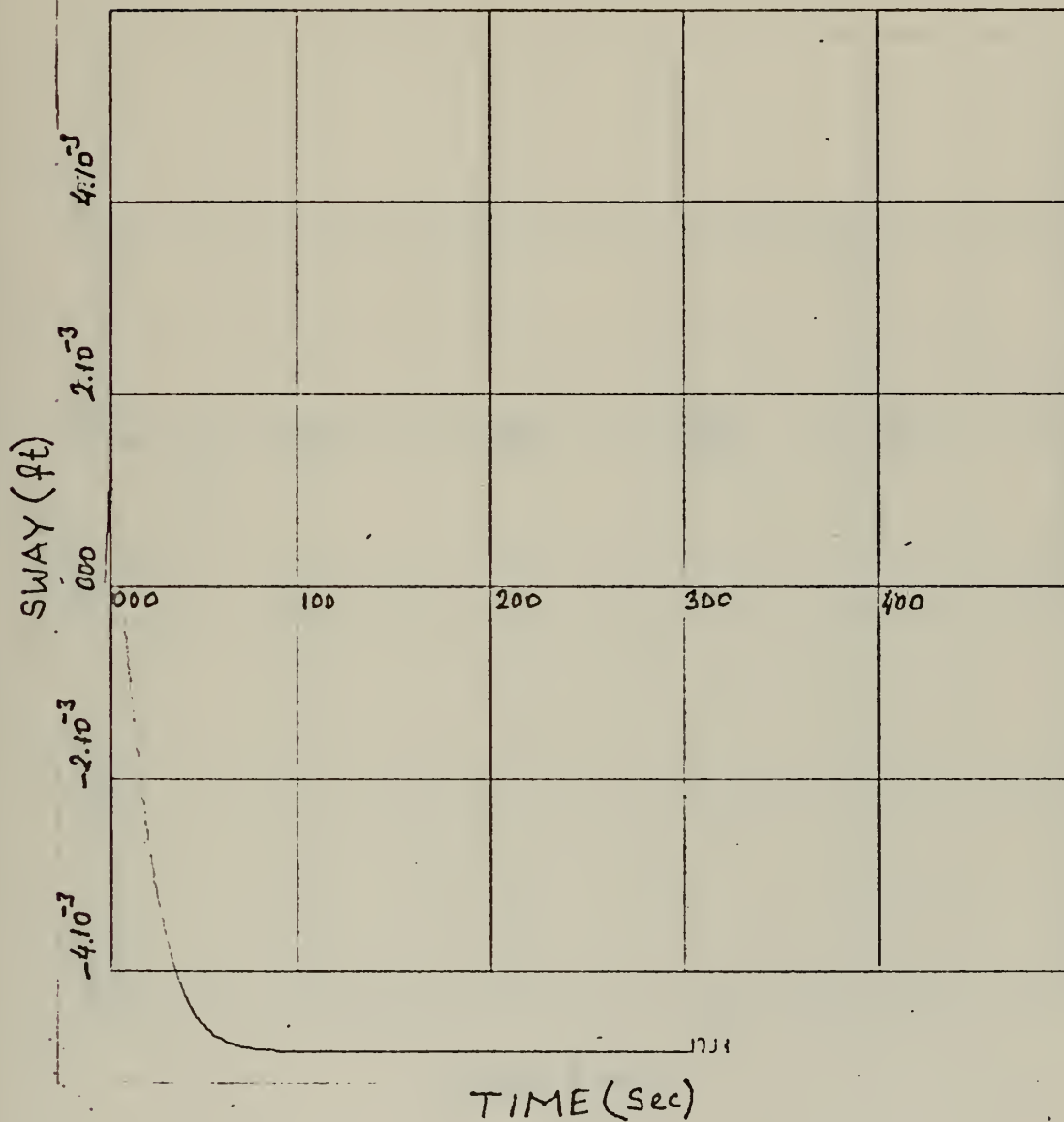


Figure 37. Variation of Sway Versus Time for Wind Direction 090° , Velocity 3 miles/hr, Automatically Steered.

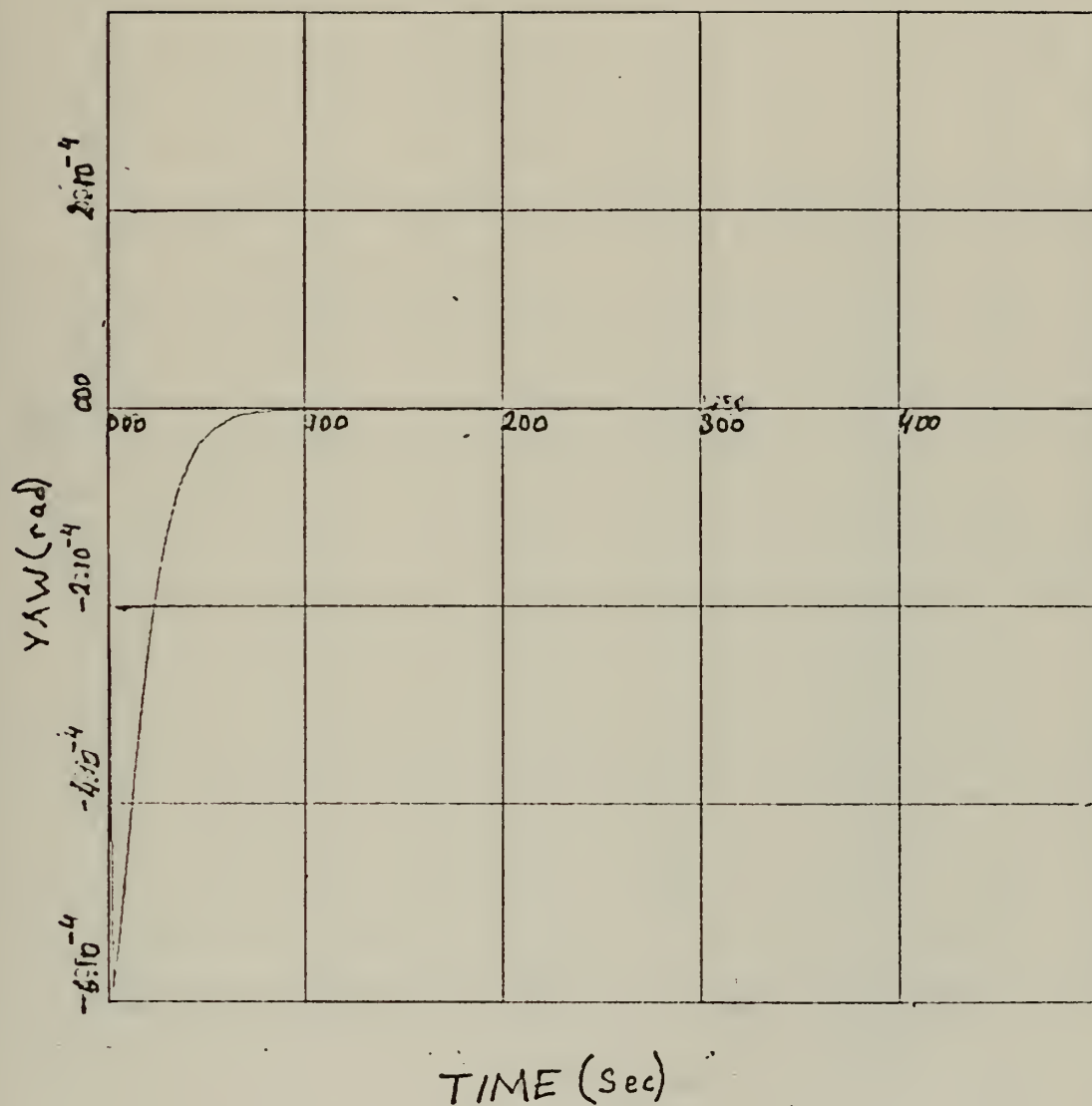


Figure 38. Variation of Yaw Versus Time for Wind Direction 180° , Velocity 1 mile/hr, Automatically Steered.

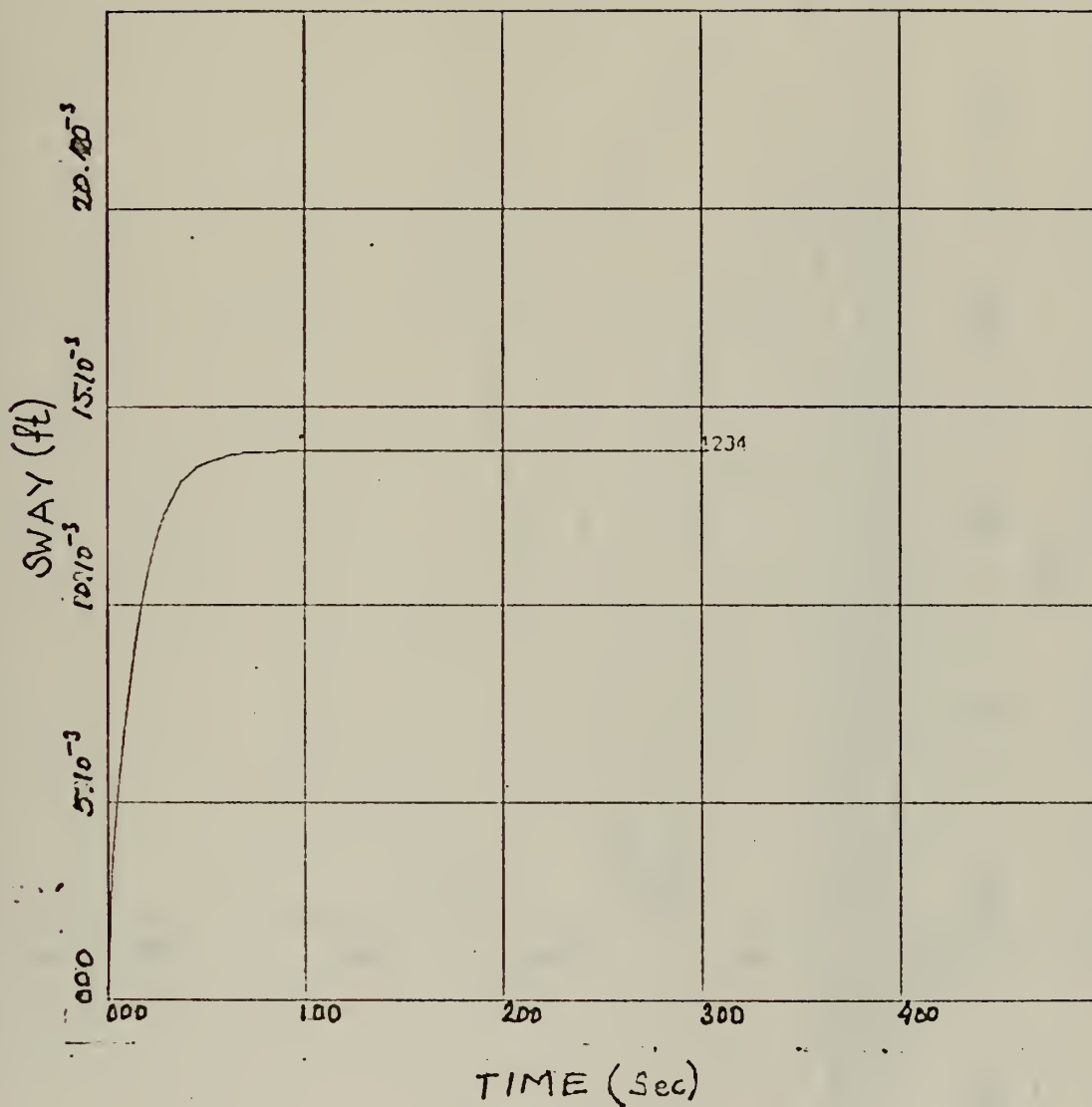


Figure 39. Variation of Sway Versus Time for Wind Direction 180° , Velocity 1 mile/hr, Automatically Steered.

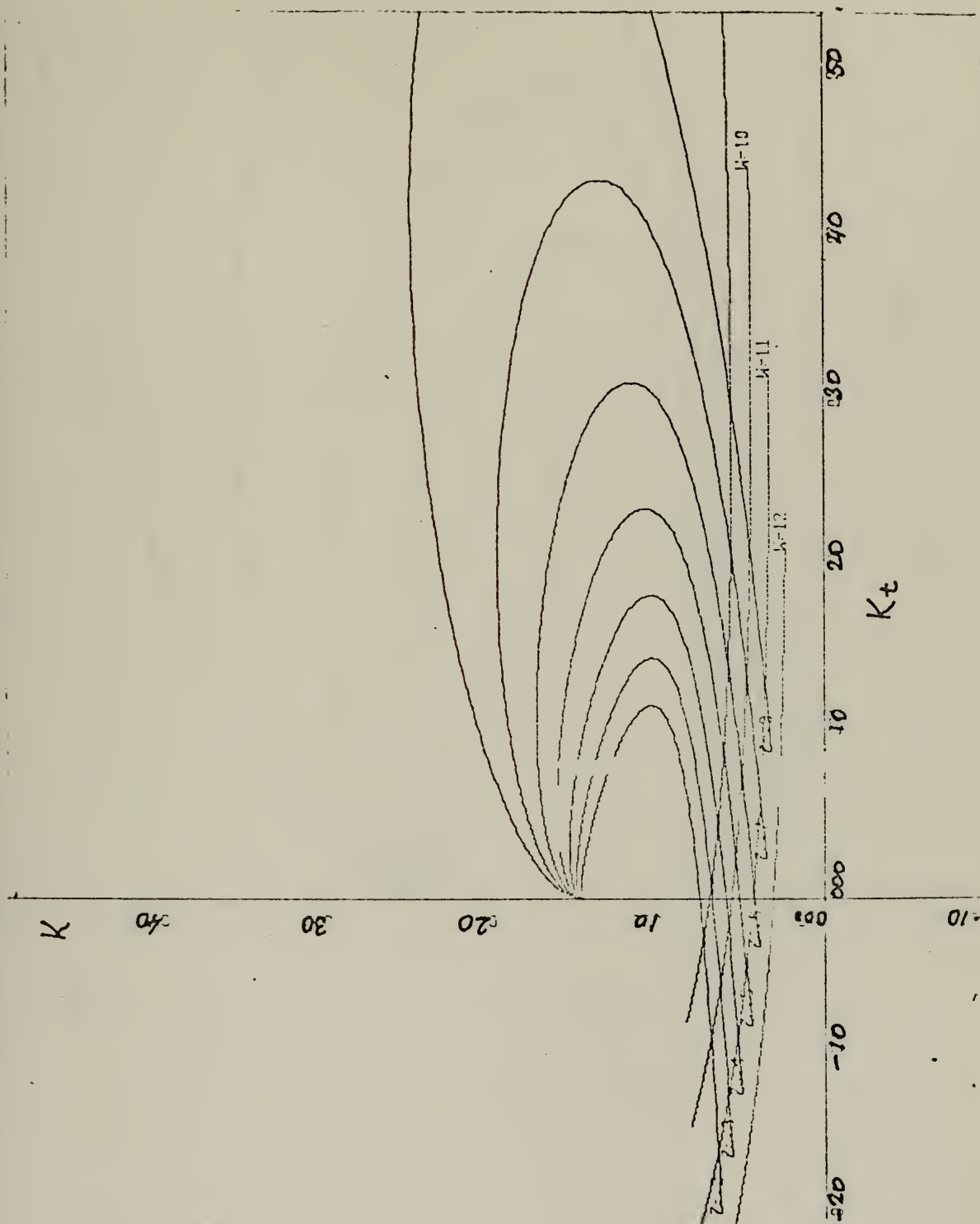


Figure 40. Yaw Gain Constant Versus Yaw Rate Gain Constant for Wind Direction 000° , Velocity 1 mile/hr.

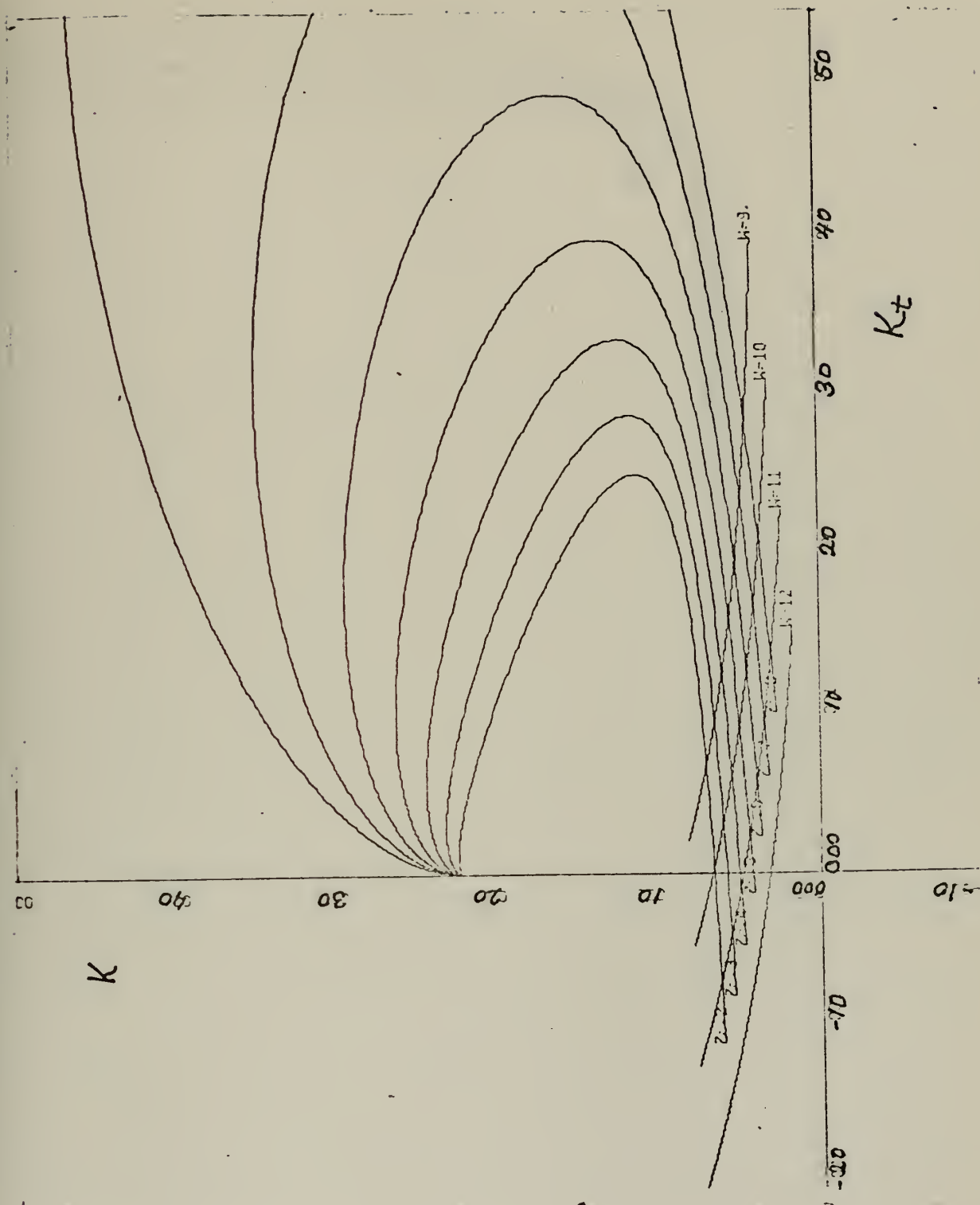


Figure 41. Yaw Gain Constant Versus Yaw Rate Gain Constant for Wind Direction 000°, Velocity 3 miles/hr.

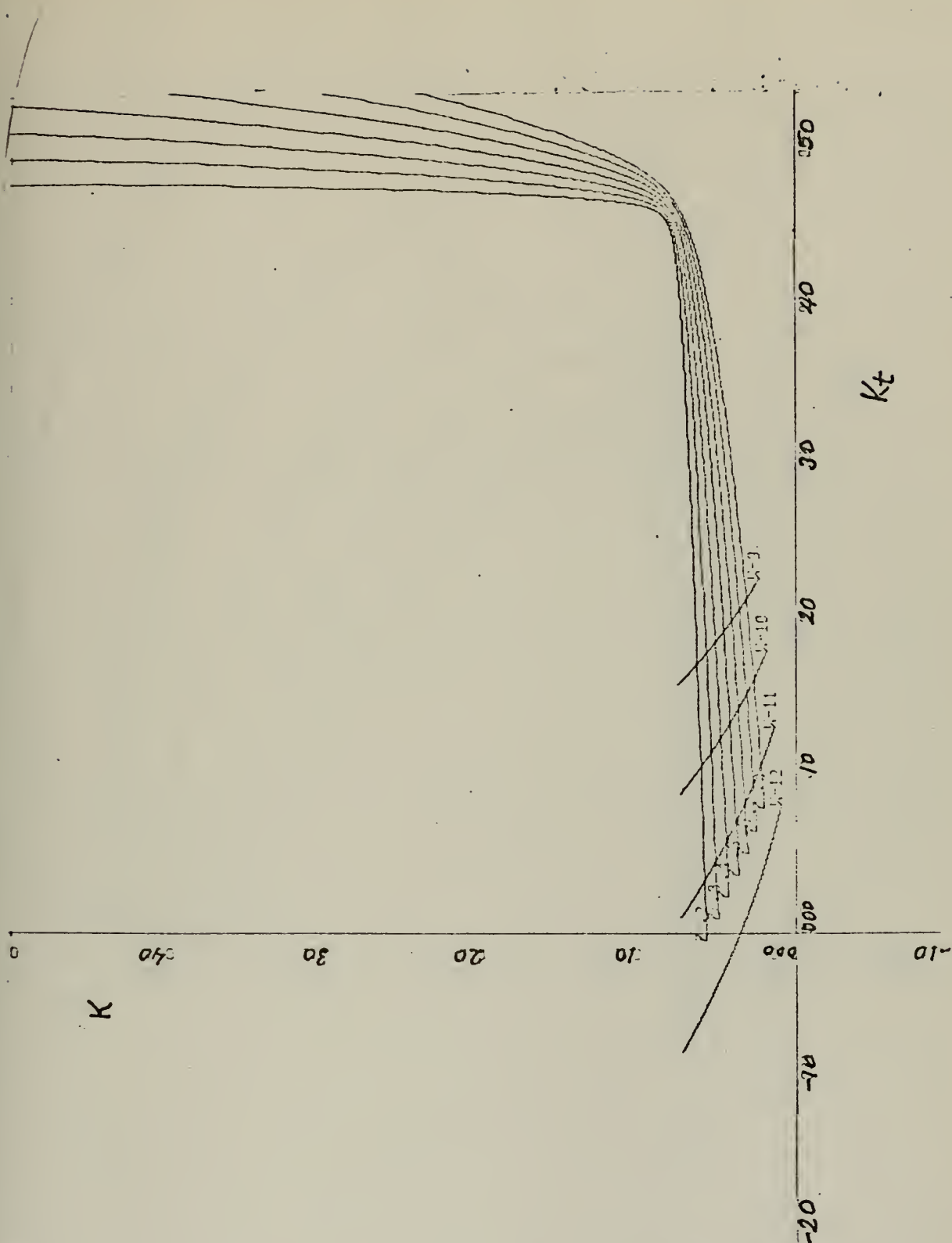


Figure 42. Yaw Gain Constant Versus Yaw Rate Gain Constant for Wind Direction 000°, Velocity 5 miles/hr.

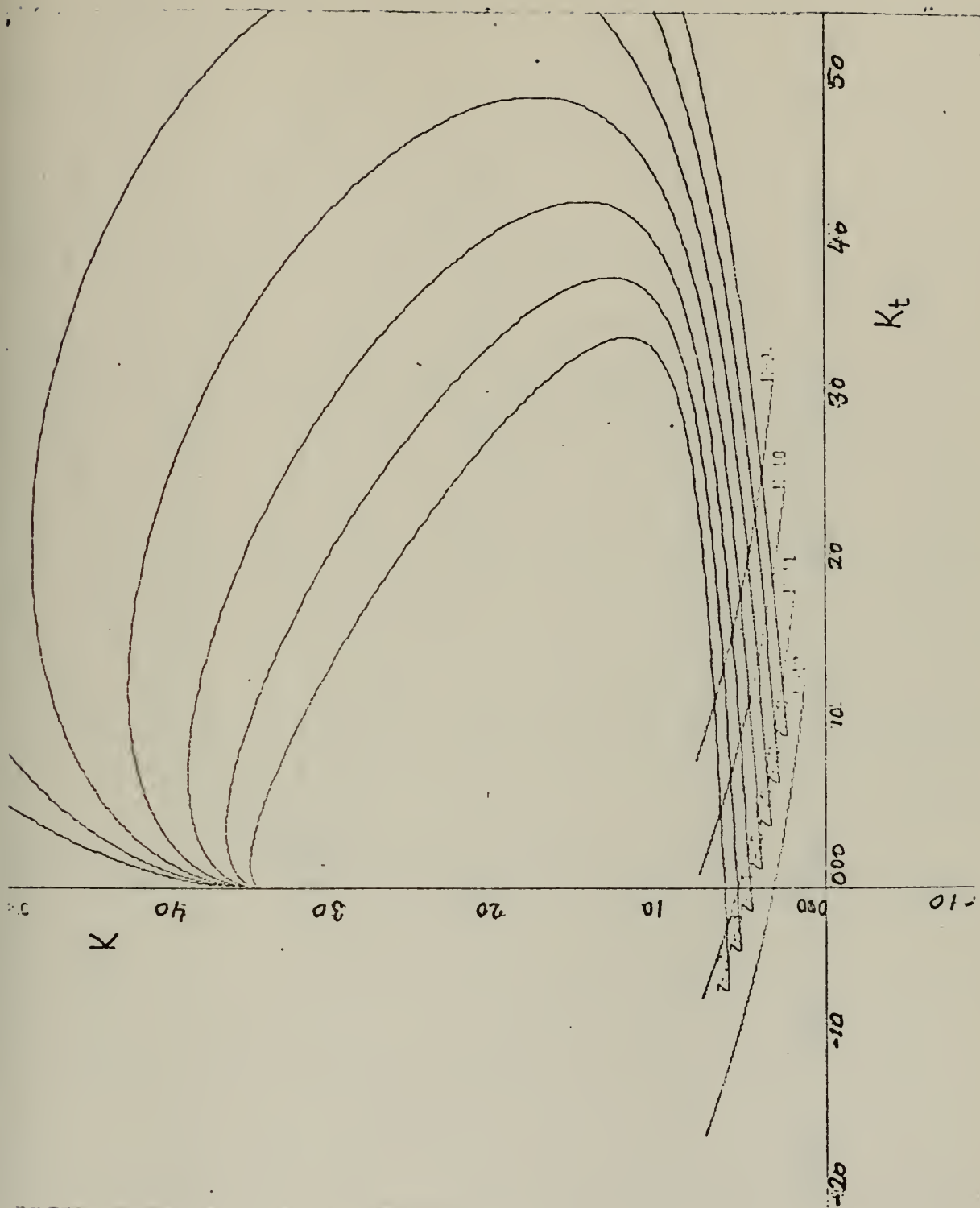


Figure 43. Yaw Gain Constant Versus Yaw Rate Gain Constant for Wind Direction 090°, Velocity 3 miles/hr.

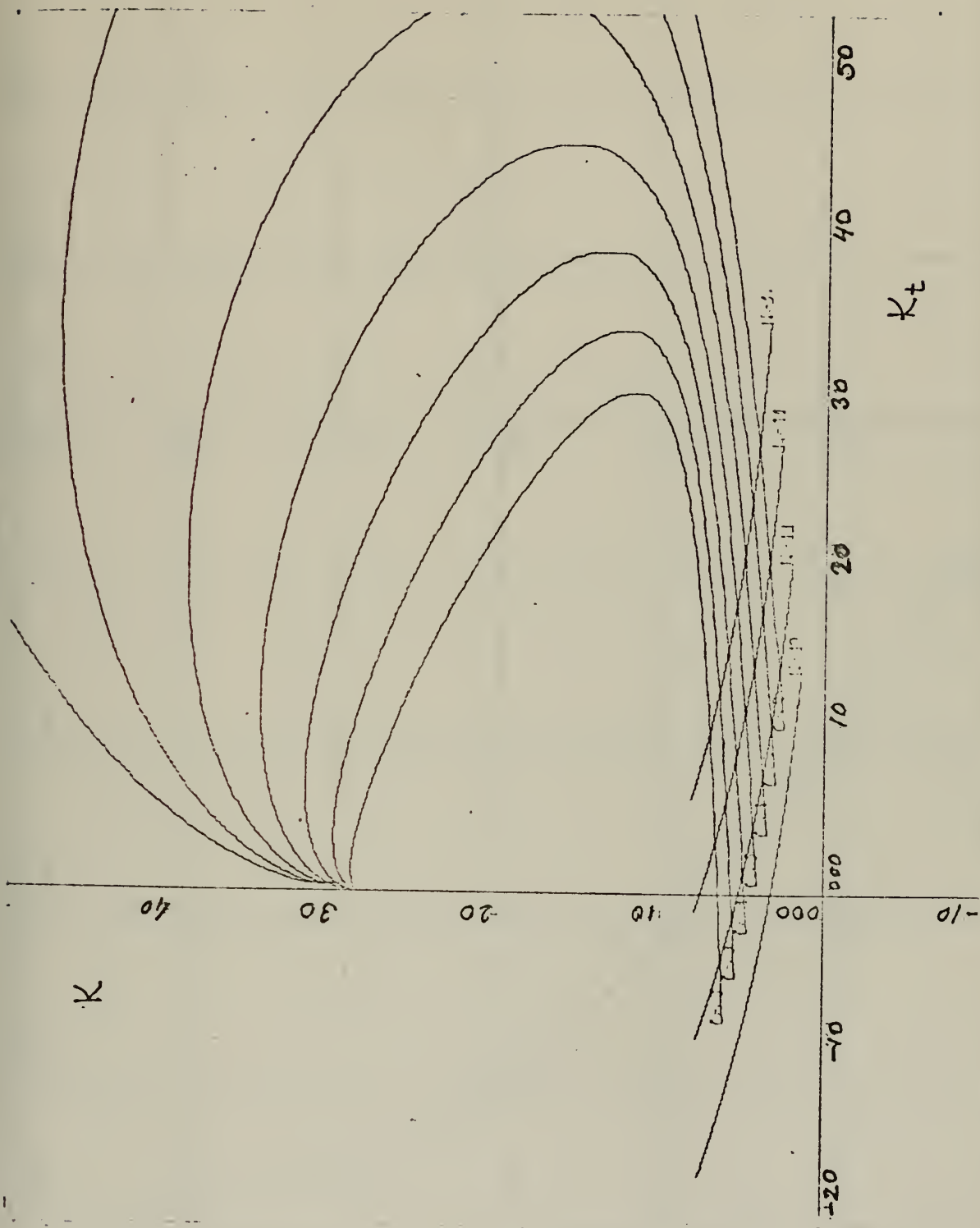


Figure 44. Yaw Gain Constant Versus Yaw Rate Gain Constant for Wind Direction 180° , Velocity 1 mile/hr.

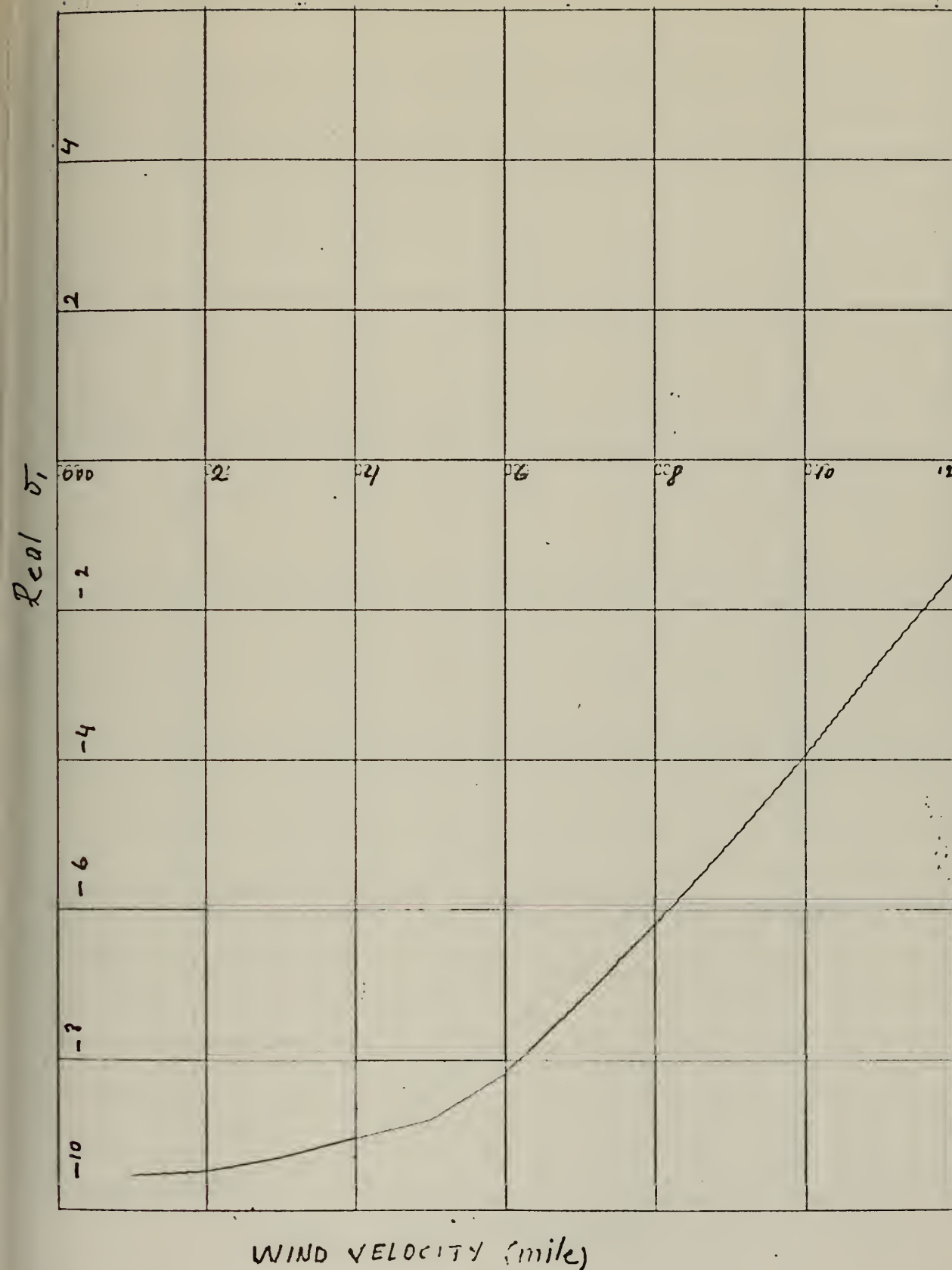


Figure 45. Real σ_1 Versus Wind Velocity for Head Wind.

Real σ_1

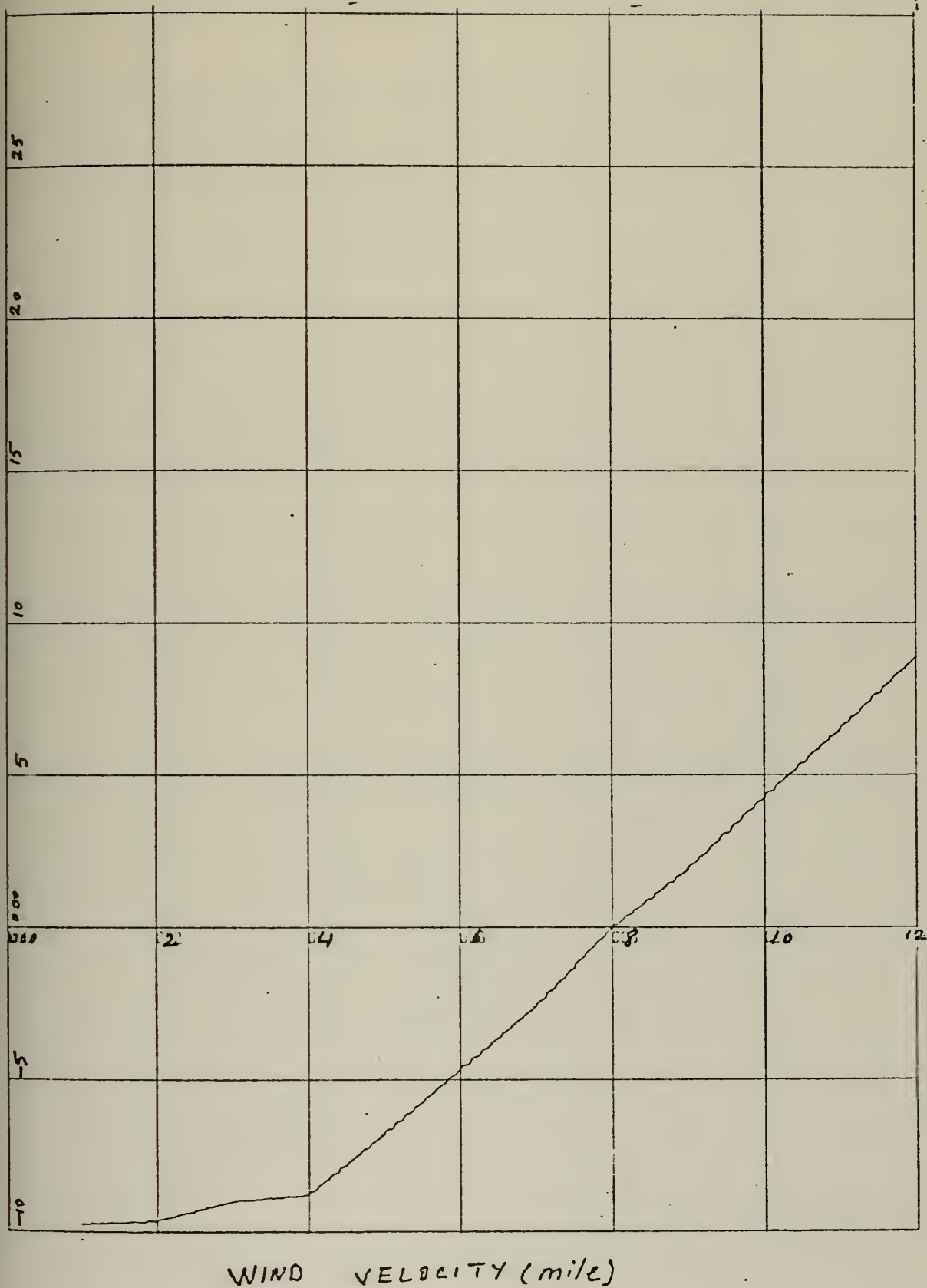


Figure 46. Real σ_1 Versus Wind Velocity for Beam Wind.

Real σ_1

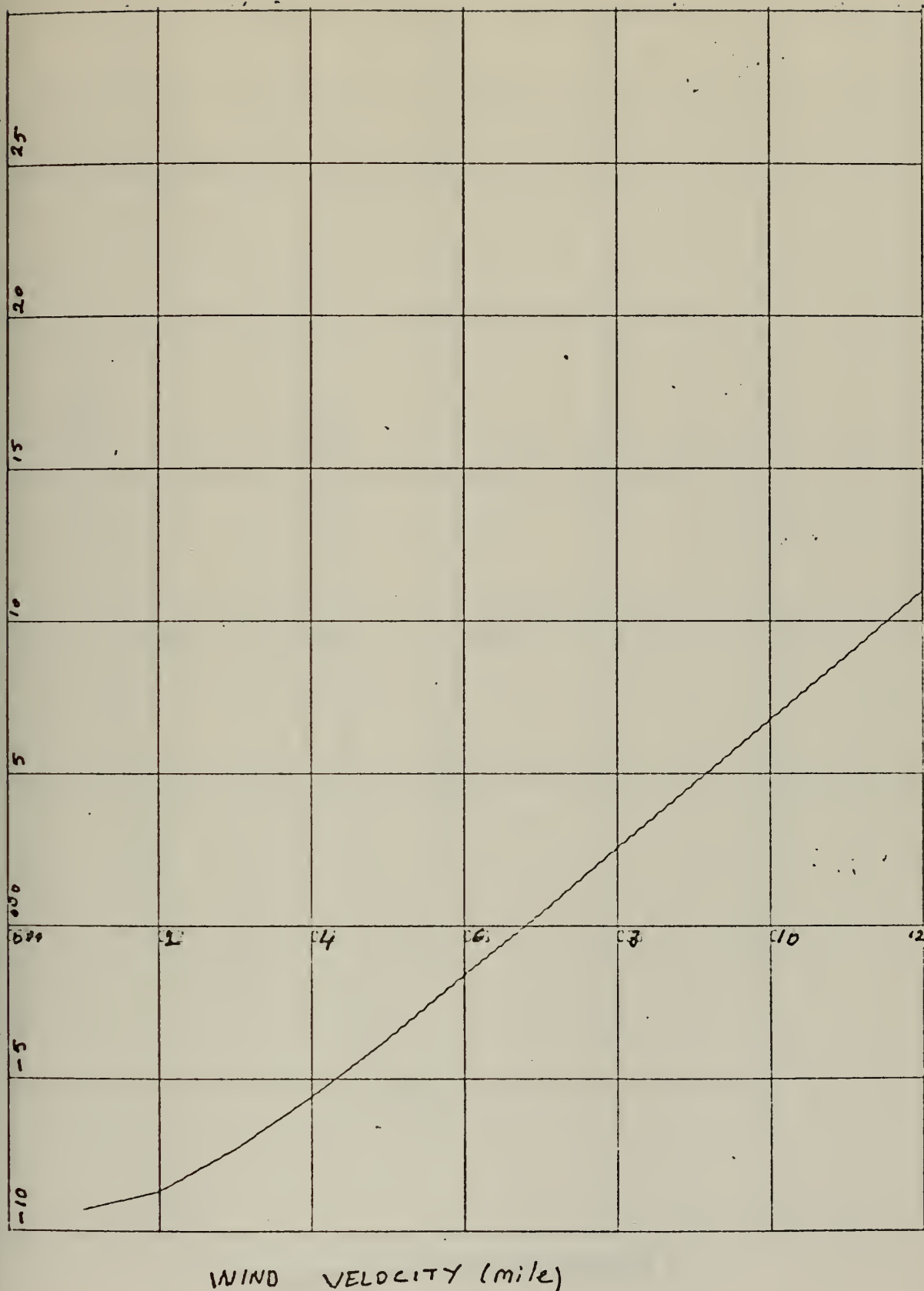


Figure 47. Real σ_1 Versus Wind Velocity for Stern Wind.

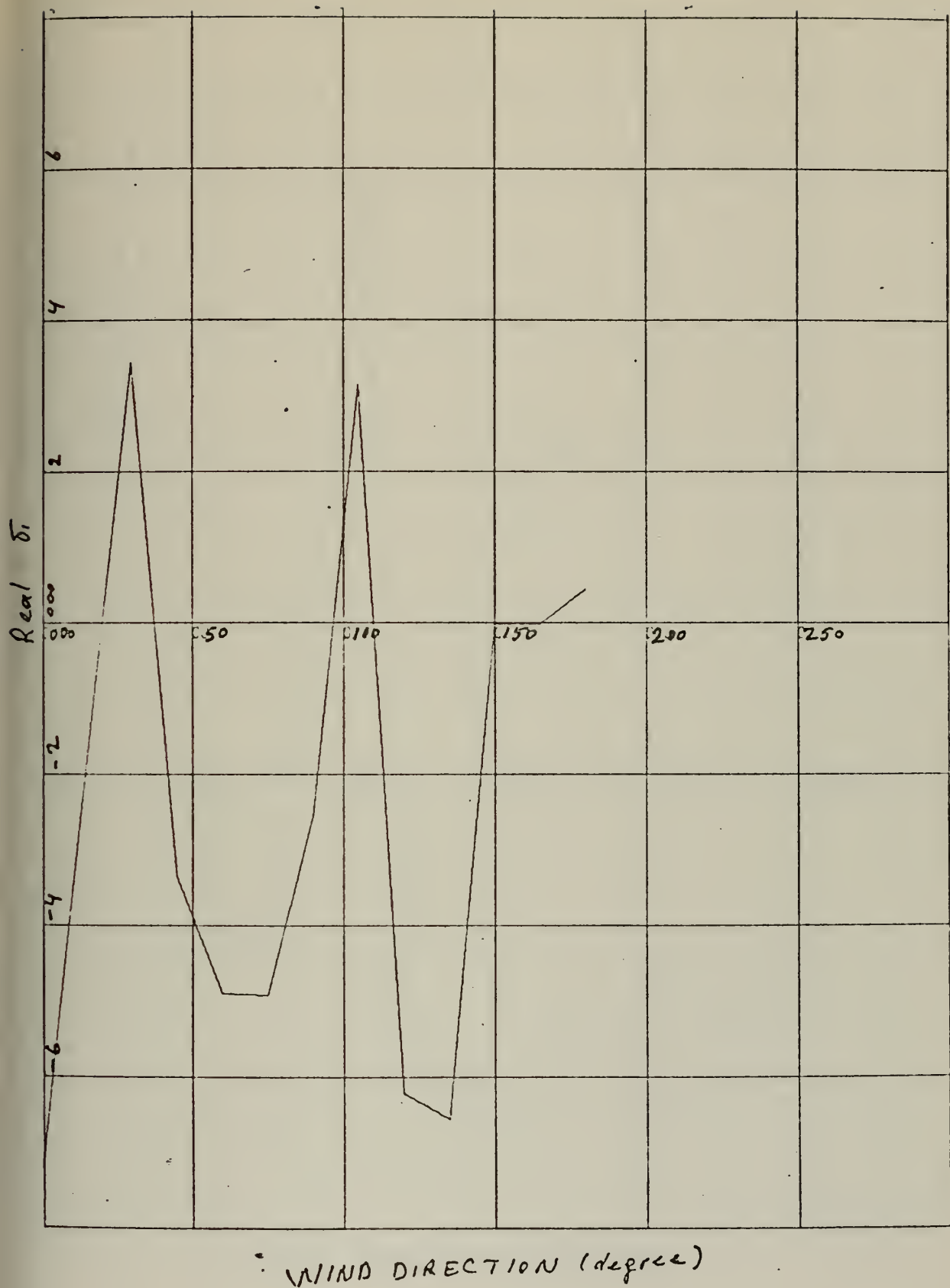


Figure 48. Real σ_1 Versus Wind Direction for 7 miles/hr Wind Velocity.

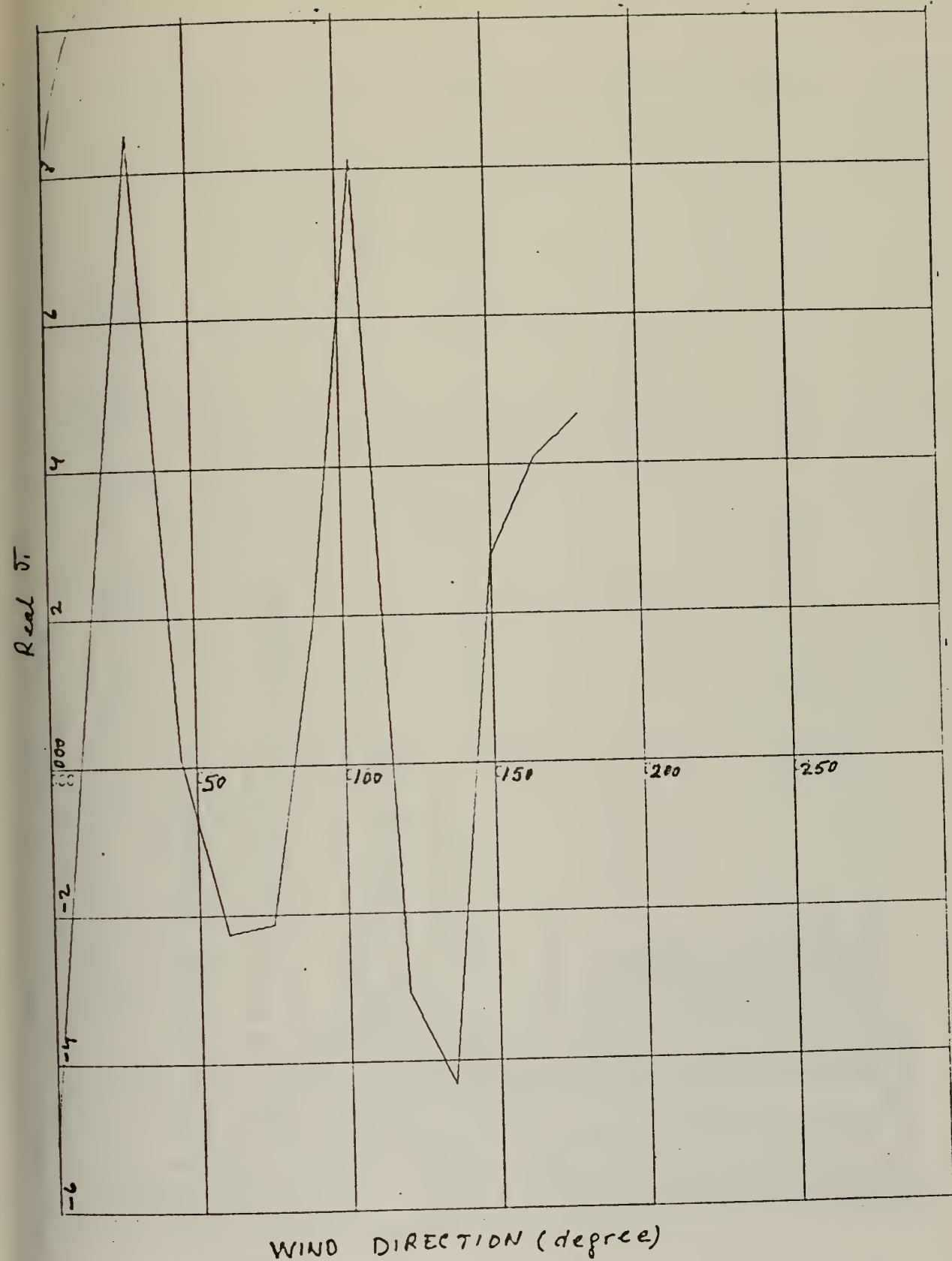


Figure 49. Real σ_1 Versus Wind Direction for 9 miles/hr Wind Velocity.


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*** PROGRAM 1 ***
** SHIP MOTION ON THE HORIZONTAL PLANE
** SHIP DEGREE OF FREEDOM EQ. OF MOTION
** THREE PLACED IN THE FOLLOWING FORM
** (ABC.S2-AAD.S-BFA)A+(000.S2-BGC.S-000)B+(000.S2-BGD.S+000)C=AAE.D
** (000.S2-BGE.S-BFD)A+(ABD.S2-BGF.S+000)B+(000.S2-BGG.S+000)C=AAE.D
** (000.S2-CAAS-BFG)A+(000.S2-BGA.S+000)B+(ABE.S2-CAB.S+000)C=CAC.D
** (000.S2-CAAS-BFG)A+(000.S2-BGA.S+000)B+(ABE.S2-CAB.S+000)C=CAC.D
** A,B,C ARE THE VARIABLES WHICH DEFINE YAW RATE, SHIP SPEED (ALONG-
** THE Y AND X AXIS) RESPECTIVELY
** D IS THE DEFLECTION OF RUDDER
** TERMINAL
** SECTION 1
** WIND VELOCITY RELATIVE TO EARTH
** PARAM YZ=1
** DIRECTION OF WIND RELATIVE TO EARTH (DEGREE)
** CONSTANT ZZZ=0.5
** CONSTANT QQQ=0.5
** YAW RATE GAIN CONSTANT IN A.C.S
** CONSTANT QQQ=1.45
** YAW GAIN CONSTANT IN A.C.S
** TIME CONSTANT OF RUDDER IN C.S
** CONSTANT QQQ=0.1
** HEADING ANGLE OF SHIP (DEGREE)
** CONSTANT ZZY=0
** DRIFT (DEGREE)
** CONSTANT YZZ=2
** SHIP SPEED
** CONSTANT YZ=1 (DEGREE)
** RUDDER DEFL. (DEGREE)
** CONSTANT ZDD=10
** CONSTANT AAB=0.089
** CONSTANT AAC=0.0506
** CONSTANT AAD=-0.071
** CONSTANT AAE=0.0252
** CONSTANT AAF=-0.0952
** CONSTANT AAG=-0.305
** CONSTANT ABA=0.0046
** CONSTANT ACA=0.017
** CONSTANT ADA=0.056
** CONSTANT AEA=-0.015
** CONSTANT ABC=0.00115
** CONSTANT ABD=0.018
** CONSTANT ABE=0.0095
** CONSTANT ABF=-0.00001
** CONSTANT DDD=0.018
** CONSTANT DDE=-0.00041
** SHIP LENGTH (FEET)
** CONSTANT ACC=5

```



```

*DISPLACEMENT (POUND)
CONSTANT ACD=36.2
*CONSTANT OF WATER (KG/MT3)
CONSTANT ACE=1000.
*CONSTANT OF AIR (KG/MT3)
CONSTANT ACF=1.29
CONSTANT ACD=0.
*SECTION 2 THIS SECTION INCLUDES FOUR PARTS
(A) PARAMETER CALCULATION OF THREE DEGREE FREEDOM EQ.
* (B) BY USING EQ. 6 THRU 20
* (C) CALCULATION FOR THE COEFF. OF NUM., OF DENOM. OF
* (D) TR. FUNC. (YAW, SWAY) FROM THREE DEGREE OF FREEDOM EQ.
* BY USING CRAMER'S RULE
* CHARACTERISTIC EQ. FOR THE PARAMETER PLANE
* POLYNOM FOR THE EIGEN VALUES
D=ZDD/57.3
* PART A
BCA=(ACD*70.63)/(ACE*2.204623*(ACC**3))
BBC=ACF/ACE
BCB=YYZ*COS(YZZ)
BCC=BCB/YYZ
BCD=ZZZ+ZZY
BCE=BCB+ZZY*COS(BCD)
BCF=YYZ*SIN(YZZ)
BCG=BCF-ZYZ*SIN(BCD)
EEE=BCE**2+BCG**2
BDA=SQRT(EEE)
BDB=BDA/YYZ
BDC=BCE/YYZ
BDE=BCG/BCE
BDG=ATAN(BDE)
BPA=BBB*BDB**2*(ABA/2*SIN(2*B DG)+ACA*SIN(BDG))
BEA=BBB*BDB**2*SIN(BDG)*ADA
BEB=BBB*BDB**2*AEA*COS(BDG)
BEC=(BEA*AAG-BBA*AAF)/(AAF*AAC-AAG*AAE)
BED=(BBA*AAG-BEA*AAF)/(AAF*AAC-AAG*AAE)
BEE=ABA*COS(2*B DG)+ACA*COS(BDG)
BEF=BDB**2-BDC
BEG=ABA/2*SIN(2*B DG)+ACA*SIN(BDG)
BFA=BBB*(BEF-2*BDB*SIN(BDG)*BEG)
BFB=-BBB*(BEE*COS(BDG)+2*BEG*SIN(BDG))
BFC=BBB*BDB*(-BEE*SIN(BDG)+2*BEG*COS(BDG))
BFD=BBB*ADA*(COS(BDG)*BEF-2*BDB*(0.5-0.5*COS(2*B DG)))
BFE=-BBB*BDB*ADA*(1.5-0.5*COS(2*B DG))
BFF=BBB*BDB*ADA*COS(BDG)*SIN(BDG)
BFG=-BBB*BDB*ADA*SIN(BDG)*SIN(BDG)
BGA=-BBB*BDB*AEA*BDB*(1.5+0.5*COS(2*B DG))
BGB=BBB*BDB*AEA*BDB*(1.5+0.5*COS(2*B DG))

```


BGC=AAF+BFB
 BGD=AAF*BEC+2*AAE*BED+BFC
 BGE=AAB-BCA
 BGF=AAG+RFE
 BGG=AAG*BEC+2*AAE*BED+BFF
 CAA=DDD+BEC
 CAB=2*DE+2*ABF*BED**2+BGB
 CAC=2*ABF*BFD
 UQQ=1/UQQ

* PART B

VVA=AAE*ABD*ABE
 VVB=AAE*BGC*ABE-AAE*ABD*CAB-AAE*BGF*ABE
 VVC=VVB+CAC*BGD*ABD
 VVD=AAE*BGC*ABE-AAE*BGG*BGA+AAE*BGF*CAB
 VVF=VVD-AAC*BGC*CAB-CAC*BGD*BGF+CAC*BGC*BGG
 SSA=AEC*ABD*ABE
 SSB=-ABC*ABD*CAB-ABC*BGF*ABE-AAD*ABD*ABE
 SSC=AAD*ABD*CAB-ABC*BGG*BGA+ABC*BGF*CAB
 SSD=+AAD*BGF*ABE-BFA*ABD*ABE-BCE*BGC*ABE
 SSE=SSC+SSD-BGD*ABD*CAA
 SSF=+AAD*BGG*BGA-AAD*BGF*CAB+BFA*ABD*CAB
 SSG=+BFA*BGF*ABE-BGE*BGD*BGA+BGE*BGC*CAB
 SAS=CAA*BGF*BGD-BFD*BGC*ABE-CAA*BGC*BGC
 SBS=SSF+SSG+SAS-BFG*BGD*ABD
 SCS=+BFA*BGC*BGA-BFA*BGF*CAB-BFD*BGD*BGA
 SES=+BFD*BGC*CAB+BFG*BGF*BGD-BGC*BGG*BFG+SCS
 WVA=ABC*AAE*ABE
 WNC=-ABC*AAE*CAB+ABC*BGG*CAC-AAD*AAE*ABE+BGE*AAE*ABE
 WWI=AAD*AAE*CAB-AAD*BGG*CAC-BFA*AAE*ABE-BGE*AAE*CAB
 WWF=WWI+BGE*BGD*CAC+BFD*AAE*ABE+CAA*AAE*BGG*AAE
 WWI=BFA*AAE*CAB-BFA*BGG*CAC-BFD*AAE*CAB+BFD*BGD*AAE
 WVB=WWI+BFG*AAE*BGG-BFG*BGD*AAE

* PART C

Z10=SSB+UQQ*SSA
 Z11=SSS+UQQ*SSB
 Z12=UQQ*VVA
 Z13=SSS+UQQ*SSS
 Z14=UQQ*VVC
 Z15=SSS+UQQ*SSS
 Z16=UQQ*VVF
 Z17=UQQ*SES

* PART D

Z1=ABC*ABD*ABE*QQQ
 Z2=ABC*ABD*ABE-ABC*ABD*CAB*QQQ-ABC*BGF*ABE*QQQ-ABD*ABD*ABE*QQQ
 S1=-ABC*ABD*ABE-ABC*BGF*ABE+ABC*BGF*CAB*QQQ
 S2=S1-AAD*ABD*ABE-BGD*ABD*CAA*QQQ
 Z3=S2+AAD*ABD*ABE*QQQ+AAD*BGF*ABE*QQQ+ABD*ABD*ABE*QQQ
 S3=ABC*BGF*CAB-AAD*ABD*ABE*QQQ-ABD*BGF*ABE-AAD*BGF*CAB*QQQ


```

***PROGRAM 2 ***
**SHIP MOTION ON THE HORIZONTAL PLANE
**THREE DEGREE OF FREEDOM EQ.OF MOTION
**ARE PLACED IN THE FOLLOWING FORM
**(ABC.S2-AAD.S-BFA)A+(000.S2-BGC.S-000)B+(000.S2-BGD.S+000)C=AAE.D
**(000.S2-BGE.S-BFD)A+(ABD.S2-BGF.S+000)B+(000.S2-BGG.S+000)C=AAE.D
**(000.S2-CAA.S-BFG)A+(000.S2-BGA.S+000)B+(ABE.S2-CAB.S+000)C=CAC.D
**A,B,C ARE THE VARIABLES WHICH DEFINE YAW RATE, SHIP SPEED(ALONG-
**THE Y AND X AXIS) RESPECTIVELY
**D IS THE DEFLECTION OF RUDDER
**SECTION 1
**WIND VELOCITY RELATIVE TO EARTH
PARAM YYZ=7.
**DIRECTION OF WIND RELATIVE TO EARTH (DEGREE)
PARAM ZZZ=90.
**YAW RATE GAIN CONSTANT IN A.C.S
PARAM QQQ=1.364
**YAW GAIN CONSTANT IN A.C.S
PARAM QQQ=1.972
**TIME CONSTANT OF RUDDER IN C.S
CONSTANT QQQQ=0.1
**HEADING ANGLE OF SHIP (DEGREE)
CONSTANT ZZZY=0.
**DRIFT (DEGREE)
CONSTANT YYZ=2.
**SHIP SPEED
CONSTANT YYZ=1. (DEGREE)
**RUDDER DEFL. (DEGREE)
CONSTANT ZDD=15
CONSTANT AAB=0.089
CONSTANT AAC=0.0506
CONSTANT AAD=-0.071
CONSTANT AAE=0.0252
CONSTANT AAF=-0.0952
CONSTANT AAG=-0.305
CONSTANT ABA=0.0046
CONSTANT ACA=0.017
CONSTANT ADA=0.056
CONSTANT AEA=-0.015
CONSTANT ABC=0.00115
CONSTANT ABD=0.018
CONSTANT ABE=0.0095
CONSTANT DDD=0.018
CONSTANT DDE=-0.00041
CONSTANT ABF=-0.0000001
**SHIP LENGTH (FEET)
CONSTANT ACC=5
**DISPLACEMENT (POUND)

```



```

CONSTANT ACD=36.2 (KG/MT3)
* DENSITY OF WATER (KG/MT3)
CONSTANT ACE=1000.
* DENSITY OF AIR (KG/MT3)
CONSTANT ACF=1.29
* SECTION 2 PARAMETER CALCULATION OF THREE DEGREE FREEDOM EQ.
BY USING EQ. 6 THRU 20
D=ZDD/57.3
QQQ=1./QQQ
BCA=(ACD*70.63)/(ACE*2.204623*(ACC**3))
BBC=ACF/ACE
BCB=YYZ*COS(YZZ)
BCD=ZZZ+ZZY
BCE=BCB+ZZY*COS(BCD)
BCF=YYZ*SIN(YZZ)
CGE=BCF-ZYZ*SIN(BCD)
EEE=CGE**2+BCG**2
BDA=SQRT(EEE)
BDB=BDA/YYZ
BDC=BCG/YYZ
BDG=ATAN(BDE)
BBA=BBB*BDB**2*(ABA/2*SIN(2*B DG)+ACA*SIN(BDG))
BEB=BBB*BDB**2*SIN(BDG)*ADA
BEC=(BBA*AAE-BBA*AAE)/(AAF*AAE-AAG*AAE)
BED=(BBA*AAE-BBA*AAE)/(AAF*AAE-AAG*AAE)
BEE=ABA*CGS(2*B DG)+ACA*CGS(BDG)
BEF=BDB**2-3DC
BEG=ABA/2*SIN(2*B DG)+ACA*SIN(BDG)
BFA=BBB*(BEE*BEG-2*BDB*SIN(BDG)*BEG)
BFB=-BDB*CGS(BDG)+2*BEG*SIN(BDG)
BFC=BBB*BDB*(-BEE*SIN(BDG)+2*BEG*CGS(BDG))
BFD=BBB*ADA*(CGS(BDG)*BEG-2*BDB*(0.5-0.5*CGS(2*B DG)))
BFE=-BBB*BDB*ADA*CGS(BDG)*SIN(BDG)
BFF=BBB*BDB*ADA*CGS(BDG)*SIN(BDG)
BFG=-BBB*AAE*SIN(BDG)*(BDB**2+BDC)
BGA=-BBB*AAE*BDB*CGS(BDG)*SIN(BDG)
BGB=BBB*AAE*BDB*(1.5+0.5*CGS(2*B DG))
BGC=AAF+BFB
BGD=AAF*BEG+2*AAE*BED+BFC
BGE=AAB-BCA
BGF=AAG+BFE
BGG=AAG*BEC+2*AAE*BED+BFF
CAA=DDD+BEC
CAB=2*DDD+2*ABF*BED**2+BGB
CAC=2*ABF*BED

```



```

*SECTION 3 -PHYSICAL DEFINITIONS
YAW=A
SWAY=K
SURGE=R
*SECTION 4 -PROGRAMMED SIMULATION
KDOT=CDDOT*SIN(YAW)+BDDOT*COS(YAW)
K=INTGRL(0.,KDOT)
RDOT=CDDOT*COS(YAW)-BDDOT*SIN(YAW)
R=INTGRL(0.,RDOT)
ADDDT=(CUFAA*I1)/DEL
ADDT=INTGRL(0.,ADDDT)
A=INTGRL(0.,ADDT)
BDDOT=(COFBB*I2)/DEL
BDDOT=INTGRL(0.01,BDDOT)
B=INTGRL(0.,BDDOT)
CDDOT=(COFCC*I3)/DEL
CDDOT=INTGRL(0.4,CDDOT)
C=INTGRL(0.,CDDOT)
COFAA=ABD*ABE
COFBB=ABC*ABE
COFCC=ABC*ABD
I1=AAD*ADDT+BFA*A+BGC*BDDOT+BGD*CDDOT+AAE*D
I2=BGE*ADDT+BFD*A+BGG*CDDOT+AAC*D
I3=CAA*ADDT+BFG*A+BGA*BDDOT+CAB*CDDOT+CAC*D
DEL=ABC*ABD*ABE
*SECTION 5 -OUTPUT CHARACTERISTICS
PRTPLOT YAW
PRTPLOT SWAY
PREPAR TIME,YAW
PREPAR TIME,SWAY
TIMER FINTIM=300.,DELT=0.1,PRDEL=0.1
END
STOP
ENDJOB

```



```

*** PROGRAM 3 ***
** SHIP MOTION ON THE HORIZONTAL PLANE
** THREE DEGREES OF FREEDOM EQ.OF MOTION
** ARE PLACED IN THE FOLLOWING FORM
** (ABC.S2-AAD.S-BFA)A+(000.S2-BGC.S-000)B+(000.S2-BGD.S+000)C=AAE.D
** (000.S2-BGE.S-BFD)A+(ABD.S2-BGF.S+000)B+(000.S2-BGG.S+000)C=AAE.D
** (000.S2-CAB.S-BFG)A+(000.S2-BGA.S+000)B+(ABE.S2-CAB.S+000)C=CAC.D
** A,B,C ARE THE VARIABLES WHICH DEFINE YAW RATE , SHIP SPEED(ALONG-
** THE Y AND X AXIS) RESPECTIVELY
**D IS THE DEFLECTION OF RUDDER
** IS THE AUTOMATICALLY STEERED SHIP (ZDD=0 )
** FOR THE AUTOMATICALLY CONTROL LOOP PROGRAM SIMULATION
**SECTION 4 -
KDOT=CDDT*SIN(YAW)+BDDT*COS(YAW)
K=INTGRL(0.,KDOT)
RDOT=CDDT*COS(YAW)-BDDT*SIN(YAW)
R=INTGRL(0.,RDOT)
ADDDT=(COFAA*I1)/DEL
ADDDT=INTGRL(0.,ADDDT)
ADDT=INTGRL(0.,ADDDT)
A=INTGRL(0.,ADDT)
BDDDT=(COFBB*I2)/DEL
BDDDT=INTGRL(0.,BDDDT)
BDDT=INTGRL(0.,BDDDT)
B=INTGRL(0.,BDDT)
CDDDT=(COFCC*I3)/DEL
CDDDT=INTGRL(0.,CDDDT)
C=INTGRL(0.,CDDT)
COFAA=ABE*ABD
COFBB=ABC*ABE
COFCC=ABC*ABD
V1=(AAD-QQ*ABC)*ADDDT+(BFA+QQ*AAD-AAE*QQ*QQ)*ADDT
V2=V1+(QQ*BFA-AAF*QQ*QQ)*A+EGC*BDDT+BGC*QQ*BDDT
I1=V2+BGD*CDDT+BGD*QQ*CDDT
V3=BGE*ADDDT+(BFD+RGE*QQ-AAC*QQ*QQ)*ADDT
V4=V3+(BFD*QQ-AAC*QQ*QQ)*A+(BGF-ABD*QQ)*BDDT
I2=V4+BGF*QQ*BDDT+BGG*CDDT+BGG*QQ*CDDT
V5=CAA*ADDDT+(BFG+CAA*QQ-CAC*QQ*QQ)*ADDT
V6=V5+(BFG*QQ-CAC*QQ*QQ)*A+BGA*BDDT+BGA*QQ*BDDT
I3=V6+(CAB-ABE*ABE
DEL=ABC*ABD*ABE
**SECTION 5 - OUTPUT CHARACTERISTICS
PRTPLOT YAW
PRTPLOT SWAY
PREPAR TIME, YAW
PREPAR SWAY
TIMER FIN TIME=90., DELT=0.02, PRDEL=0.2
END
STOP

```



```

C01
C02
C03
C04
C05
C06
C07
C08
C09
C10
C11
C12
C13
C14
C15
C16
C17
C18
C19
C20
C21
C22
C23
C24
C25
C26
C27
C28
C29
C30
C31
C32
C33
C34
C35
C36
C37
C38
C39
C40
C41
C42
C43
C44
C45
C46
C47
C48

```

 PARAMETER PLANE USING MATRIX METHODS
 PARAM M

 PROGRAM PARAM M CALCULATES AND PLOTS CURVES ON THE TWO DIMENSIONAL
 PARAMETER PLANE OF EITHER:
 1) CONSTANT SIGMA(FNC OMEGA) AND/OR CONSTANT OMEGA(FNC SIGMA);
 2) CONSTANT ZETA(FNC OMEGA(N)) AND/OR CONSTANT OMEGA(N)(FNC ZETA);
 3) SIGMA (REAL ROOT) LINES;
 4) A COMBINISTIC EQUATION OF 1 AND 3 OR 2 AND 3 ABOVE;
 FOR CHARACTERISTIC EQUATIONS OF THE TYPE
 $A(O) + A(1)*S - A(N-2)*S*(N-2) + A(N-1)*S*(N-1) + S*N$
 WHERE THE A COEFFICIENTS ARE OF THE LINEAR FORM
 $B*ALPHA + C*BETA + D$ AND D CONSTANT.
 IN ADDITION, PROVISIONS ARE INCLUDED IN THE PROGRAM TO COMPUTE THE
 ROOTS OF THE REDUCED CHARACTERISTIC EQUATION FOR THE GIVEN SIGMA
 AND OMEGA OR ZETA AND OMEGA(N) TO ALLOW FOR SHADING (STABILITY) OF
 THE PARAMETER PLANE.

 DEFINITION OF SYMBOLS USED FOR INPUT DATA *****

 NT= TYPE OF OUTPUT CURVES DESIRED
 1=CONSTANT SIGMA(FNC OMEGA) AND/OR CONSTANT OMEGA(FNC SIGMA)
 2=CONSTANT ZETA(FNC OMEGA(N)) AND/OR CONSTANT OMEGA(N)(FNC ZETA)
 3=SIGMA(REAL ROOT) LINES
 4=COMBINATION OF 1 AND 3 ABOVE
 5=COMBINATION OF 2 AND 3 ABOVE
 NOTE: ALL CURVES ARE PLOTTED ON PLAIN PAPER. IF A 1 INCH GRID
 IS DESIRED REPLICATE EQUATION (1) > NO > 1)
 ORDER OF DECADRE SPANNED BY OMEGA OR OMEGA(N) IF NT=1,2,4,5
 NO= NO. OF DECADES SPANNED BY OMEGA OR OMEGA(N) IF NT=1,2,4,5
 NL= LARGEST SIGMA/ZETA FOR CONSTANT OMEGA/OMEGA(N) CURVES IF NT=2,5
 NZ= NO. OF CONSTANT SIGMA CURVES IF NT=1,4; ZETA CURVES IF NT=2,5
 NW= NO. OF CONSTANT OMEGA CURVES IF NT=1,4; OMEGA(N) CURVES IF NT=2,5
 NS= NO. OF SIGMA(REAL ROOT) LINES IF NT=3,4,5
 IP= PRINTED OUTPUT PT EACH CURVE PLUS SUB PLOT PTS IF STABILITY CHANGES
 1=FIRST PLOT PT
 2=OUTPUT EVERY TENTH PLOT PT (MAX OF 300+100*(NO-2) LINES PER CURVE)
 3=OUTPUT EVERY TENTH PLOT PT (300+100*(NO-2) LINES PER CURVE)
 4=OUTPUT EVERY TENTH PLOT PT (300 LINES PER CURVE)
 5=OUTPUT EVERY TENTH PLOT PT (300 LINES PER CURVE)
 6=OUTPUT EVERY TENTH PLOT PT (300 LINES PER CURVE)
 7=NO PRINTED OUTPUT PT
 IX= DISTANCE IN INCHES OF THE X-AXIS FROM THE BOTTOM OF THE GRAPH
 IY= DISTANCE IN INCHES OF THE Y-AXIS FROM LEFT SIDE OF THE GRAPH
 WS= START VALUE OF OMEGA/OMEGA(N) FOR CONSTANT SIGMA/ZETA CURVES
 XS= X-SCALE IN UNITS PER INCH (CANNOT BE ZERO)
 YS= Y-SCALE IN UNITS PER INCH (CANNOT BE ZERO)
 LZ= LABELS FOR CONSTANT: SIGMA(NI=1,4) OR ZETA (NI=2,5) CURVES


```

C96
C97
C98
C99
C100
C101
C102
C103
C104
C105
C106
C107
C108
C109
C110
C111
C112
C113
C114
0002
0003
0004
0005
0006
TEMP
0007
0008
0009
0010
0011
0012
0013
0014
0015
0016
0017
0018
0019
0020
0021
0022
0023
0024
0025
0026
0027
0028
0029

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```

ERROR READOUTS: SINGULAR POINT
1: POSSIBLE: MATRIX BEING INVERTED EITHER SINGULAR OR NEARLY SO:
MEANING: COEFF OF REDUCED CHAR. EQN. TO DETERMINE ROOTS WITH 500
2: POLRT ERROR: SUBROUTINE POLRT UNABLE TO STARTING VALUES: COEFFICIENTS ARE
MEANING: ITERATIONS ON 5 STARTING VALUES: PRINTED OUT FOR CONVENIENCE:

```

```

***
TEMPORARY RESTRICTION
DUE TO SOME AS YET UNDETERMINED QUIRK, AN ERROR IN THE POLRT SUB-
ROUTINE PERIODICALLY CAUSES AN ERROR INTERRUPT WHICH IN THE MVT MODE
OF OPERATION ON THE IBM 360 SELF CORRECTS ITSELF. UNTIL SUCH TIME
AS THIS DISCREPANCY CAN BE ELIMINATED, THIS PROGRAM MUST BE RUN ON MVT
ONLY. IF ANY SUCH INTERRUPTS OCCUR, THE FOLLOWING MESSAGE WILL
APPEAR AT THE END OF THE PRINT OUT:
SUMMARY OF ERRORS FOR THIS JOB ERROR NUMBER "NO. ERRORS"
209

```

```

REAL*8 ITITLE(12) /,GG(10)/1,0076,1.016,1.0245,1.0312,1.0394,
REAL LABEL/4H /,0633,1.071,1.078/, AK(10),LZ(20),LW(20),
*1.0483,1.0568,1.0633,1.071,1.078/, SIG(20),CK(10),BK(10),AA(100),
**LS(20),SZ(20),WNN(20),SIG(20),CK(10),BK(10),DK(10),AA(100),
*COEF(9),COF(9),ROOTR(8),ROOTI(8),ALFA(300),BETA(300),SIGP(10)
CALL ERRSET (207,256,-1,1,0,209)
WRITE(6,500)

```

```

WRITE(6,500)
READ(5,400)(ITITLE(I),I=1,12)
WRITE(6,401)(ITITLE(I),I=1,12)
WRITE(5,402) NT,NO,ND,NL,NZ,NW,NS,IP,IX,IY,WN,XS,YS
WRITE(6,501) NT,NO,ND,NL,NZ,NW,NS,IP,IX,IY,WN,XS,YS
WRITE(6,411) NT,NO,ND,NL,NZ,NW,NS,IP,IX,IY,WN,XS,YS

```

```

IF(NT.LE.5) GO TO 200

```

```

IG=1
IF(NT-10
NT=NT-10
M1=NO+1
M2=NO-2
M3=NO-1
READ(5,403)(LZ(I),I=1,NZ)
WRITE(6,502)
WRITE(6,404)(LZ(I),I=1,NZ)
READ(5,403)(LW(I),I=1,NW)
WRITE(6,503)
WRITE(6,404)(LW(I),I=1,NW)
READ(5,403)(LS(I),I=1,NS)
WRITE(6,504)
WRITE(6,404)(LS(I),I=1,NS)
READ(5,405)(SZ(I),I=1,NZ)

```

200

CCCCCCCCCCCCCCCCCCCC

0030
0031
0032
0033
0034
0035
0036
0037
0038
0039
0040
0041
0042
0043
0044
0045
0046
0047
0048
0049
0050
0051
0052
0053
0054
0055
0056
0057
0058
0059
0060
0061
0062
0063
0064
0065
0066
0067
0068
0069
0070
0071
0072
0073
0074
0075
0076
0077

```

WRITE(6,505) (SZ(I),I=1,NZ)
WRITE(6,406) (SZ(I),I=1,NZ)
READ(5,405) (WWN(I),I=1,NW)
WRITE(6,506) (WWN(I),I=1,NW)
WRITE(6,406) (WWN(I),I=1,NW)
READ(5,405) (SIG(I),I=1,NS)
WRITE(6,507) (SIG(I),I=1,NS)
WRITE(6,406) (SIG(I),I=1,NS)
READ(5,405) (CK(M1-I),I=1,NO)
WRITE(6,508) (CK(M1-I),I=1,NO)
WRITE(6,406) (CK(M1-I),I=1,NO)
READ(5,405) (AK(M1-I,1),I=1,NO)
WRITE(6,509) (AK(M1-I,1),I=1,NO)
WRITE(6,406) (AK(M1-I,1),I=1,NO)
READ(5,405) (AK(M1-I,2),I=1,NO)
WRITE(6,510) (AK(M1-I,2),I=1,NO)
WRITE(6,406) (AK(M1-I,2),I=1,NO)
MOD=1
XLIMP=(9.2-1Y)*XS
YLIMP=(15.2-1X)*YS
YLIMN=-1Y*XS
YLIMN=-1X*YS
IF(NZ.EQ.2) GO TO 202
DO 101 I=1,NO
DO 100 J=1,M2
AK(I,J)=0.0
BK(I)=0.0
DO 102 I=1,M2
AK(I,I+2)=-1.0
GO TO (103,103,147,103,103),NT
DO 146 JJ=1,2
GO TO (204,205),JJ
IF(NZ.EQ.0) GO TO 146
NI=NZ
G=GG(ND)
WRITE(6,526)
GO TO 206
IF(NW.EQ.0) GO TO 146
NI=NW
DEL=NL/300.0
WRITE(6,526)
DO 145 K=1,NI
GO TO (104,207),JJ
W=WN
SIGZ=SZ(K)
GO TO 105
SIGZ=0.0
W=WN(K)

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105  LL=0
      LLL=0
      LLLL=0
      IPSET=0
      DO 242 L=1,300
      IPP=0
      GO TO (106,109,146,106,109),NT
106  IF(L.GT.1) GO TO 607
306  GO TO (306,307),JJ
      WRITE(6,511)
      WRITE(6,513)
      GO TO 607
307  WRITE(6,512)
      WRITE(6,513)
607  IF(NO.EQ.2) GO TO 208
      DO 107 I=2,M3
107  AK(I,I+1)=-2.0*SIGZ
      DO 108 I=3,NO
108  AK(I,I)=- (SIGZ**2 + W**2)
208  BK(1)=2.0*SIGZ
      BK(2)=SIGZ**2+W**2
      GO TO 112
109  IF(L.GT.1) GO TO 310
209  GO TO (209,210),JJ
      WRITE(6,522)
      WRITE(6,524)
      GO TO 310
210  WRITE(6,523)
      WRITE(6,524)
310  IF(NO.EQ.2) GO TO 211
110  DO 110 I=2,M3
      AK(I,I+1)=-2.0*SIGZ*W
111  DO 111 I=3,NO
      AK(I,I)=-W**2
211  BK(1)=2.0*SIGZ*W
      BK(2)=W**2
112  DO 113 I=1,NO
113  DK(I)=BK(I)-CK(I)
      II=0
      DO 115 I=1,NO
      DO 114 J=1,NO
      II=II+1
114  AA(II)=AK(J,I)
115  CONTINUE
      CALL SIMQ(AA,DK,NO,KS)
      KS=KS+1
      GO TO (117,116),KS
116  WRITE(6,407)SIGZ,W

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117 GO TO 240
    ATEMP=DK(1)
    BTEMP=DK(2)
    IF(L.GT.1) GO TO 217
    AMAX=ATEMP
    AMIN=ATEMP
    BMAX=BTEMP
    BMIN=BTEMP
    217 IF(ATEMP.GE.AMIN) GO TO 317
    317 IF(ATEMP.LE.AMAX) GO TO 417
    417 IF(BTEMP.GE.BMIN) GO TO 617
    617 IF(BTEMP.LE.BMAX) GO TO 717
    717 BMAX=BTEMP
    IF(NO.EQ.2) GO TO 218
    DO 118 I=1,M2
    118 COEF(I)=DK(M1-I)
    COEF(M3)=1.0
    218 IF(XLIMN-ATEMP) 119,119,123
    119 IF(YLIMN-XLIMP) 120,120,123
    120 IF(YLIMN-BTEMP) 121,121,123
    121 IF(BTEMP-YLIMP) 122,122,123
    122 LL=LL+1
    LLL=LLL+1
    GO TO (125,125,125,138,234,140),IP
    123 GO TO (240,240,124,124,124,240),IP
    124 IPP=1
    GO TO (125,125,125,138,234,142),IP
    125 IF(NO.GT.3) GO TO 225
    IF(NO.EQ.2) GO TO 127
    ROOTR(1)=-DK(3)
    ROOTI(1)=0.0
    GO TO 127
    225 CALL POLRT(COEF,COF,M2,ROOTR,ROOTI,IER)
    IERROR=IER+1
    GO TO(127,126,126,126),IERROR
    126 WRITE(6,408)ATEMP,BTEMP,SIGZ,W
    WRITE(6,412) (COEF(M3+1-I),I=1,M3)
    IF(LL.GT.1) GO TO 139
    IPSET=1
    GO TO 139
    127 GO TO (128,128,138,138,138,138,142),IP
    128 ISTAB=0
    IF(NO.EQ.2) GO TO 130
    DO 130 J=1,M2
    IF(ROOTR(I)) 130,130,129

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244 WRITE(6,514) SIGZ
WRITE(6,525) AMAX,BMAX,AMIN,BMIN
GO TO 145
344 WRITE(6,521) W
WRITE(6,525) AMAX,BMAX,AMIN,BMIN
145 CONTINUE
146 CONTINUE
147 GO TO (165,165,148,148),NT
148 GO TO (248,248,248,248,248,249),IP
248 WRITE(6,515)
249 DO 164 K=1,NS
DO 149 I=1,NO
SIGP(I)=SIG(K)**I
ACOEFF=AK(NO,1)
BCOEFF=AK(NO,2)
CCOEFF=SIGP(NO)+CK(NO)
DO 150 I=1,M3
ACOEFF=ACOEFF+AK(I,1)*SIGP(NO-I)
BCOEFF=BCOEFF+AK(I,2)*SIGP(NO-I)
CCOEFF=CCOEFF+CK(I)*SIGP(NO-I)
150 SLOPE=-BCOEFF/ACOEFF
AINTER=-CCOEFF/ACOEFF
GO TO (250,250,250,250,250,164),IP
250 WRITE(6,516) SIG(K),SLOPE,AINTER
J=1
ALFA(J)=SLOPE*YLMN+AINTER
IF(XLMN-ALFA(J)) 151,151,153
151 IF(ALFA(J)-XLMN) 152,152,153
152 BETA(J)=YLMN
J=J+1
ALFA(J)=SLOPE*YLMN+AINTER
IF(XLMN-ALFA(J)) 154,154,156
154 IF(ALFA(J)-XLMN) 155,155,156
155 BETA(J)=YLMN
IF(J.EQ.2) GO TO 162
J=J+1
156 BETA(J)=(1.0/SLOPE)*XLMN-AINTER/SLOPE
IF(YLMN-BETA(J)) 157,157,159
157 IF(BETA(J)-YLMN) 158,158,159
158 ALFA(J)=XLMN
IF(J.EQ.2) GO TO 162
J=J+1
159 BETA(J)=(1.0/SLOPE)*XLMN-AINTER/SLOPE
IF(YLMN-BETA(J)) 160,160,163
160 IF(BETA(J)-YLMN) 161,161,163
161 ALFA(J)=XLMN
IF(J.LT.2) GO TO 163
162 CALL DRAW(2,ALFA,BETA,MOD,0,LS(K),ITITLE,XS,YS,IX,IY,2,2,

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514 FORMAT(T8,'CURVE FOR CONSTANT SIGMA/ZETA =',E13.5,T53,'WAS NOT PLO
*TTED.',/,T8,'AS LESS THAN TWO POINTS WERE GENERATED WITHIN SPECIFIE
*D GRAPH RANGE',/)
515 FORMAT(I1,/,T25,'SIGMA (REAL ROOT) LINES',/)
516 FORMAT(T3,/,FOR SIGMA =',E12.5,T27,': ALPHA = ',E12.5,T50,
*'* BETA + ',E12.5,/)
517 FORMAT(T3, 'REAL ROOT LINE FOR SIGMA =',E13.5,T42,'LIES OUTSIDE THE
* SPECIFIED GRAPH RANGE',/)
518 *T3, 'POINTS GENERATED BY THE PROGRAM LIE',/,
*T3, 'OF THE SPECIFIED GRAPH REGION. CHECK THE VALUES OF',/,
*T3, 'XS AND YS AS WELL AS IX AND IY ON DATA CARD 3',/)
519 FORMAT(T8,'FOR THE CURVE OF CONSTANT OMEGA/OMEGA(N) =',E13.5,
/,I10,T12,
* 'POINTS OUT OF A POSSIBLE 300 LIE WITHIN SPECIFIED GRAPH RANGE',/)
520 FORMAT(T8,'FOR THE CURVE OF CONSTANT SIGMA/ZETA =',E13.5,
/,I10,T12,
* 'POINTS OUT OF A POSSIBLE 300 LIE WITHIN SPECIFIED GRAPH RANGE',/)
521 *FORMAT(T8,'CURVE FOR CONSTANT OMEGA/OMEGA(N) =',E13.5,T57,'WAS NOT
* PLOTTED.',/,T8,'AS LESS THAN TWO POINTS WERE GENERATED WITHIN SPEC
* IFIED GRAPH RANGE',/)
522 *FORMAT(///,T19,'CONSTANT ZETA CURVE ',T81,'CORRESPONDING REMAINING
* ROOTS',/)
523 *FORMAT(///,T17,'CONSTANT OMEGA(N) CURVE ',T81,'CORRESPONDING REMAI
*NING ROOTS',/)
524 *FORMAT(T7,'ALPHA',T21,'BETA',T35,'ZETA',T48,'OMEGA(N)',T64,'REAL',
*T76,'IMAG',T88,'REAL',T100,'IMAG',T112,'REAL',T124,'IMAG',/)
525 *FORMAT(T8,'MAXIMUM AND MINIMUM GENERATED ALPHA & BETA VALUES WERE:
*,/,T8,'AMAX=',E10.3,T24,'BMAX=',E10.3,T40,'AMIN=',E10.3,T56,
* 'BMIN=',E10.3,/)
526 *FORMAT(I1)
END

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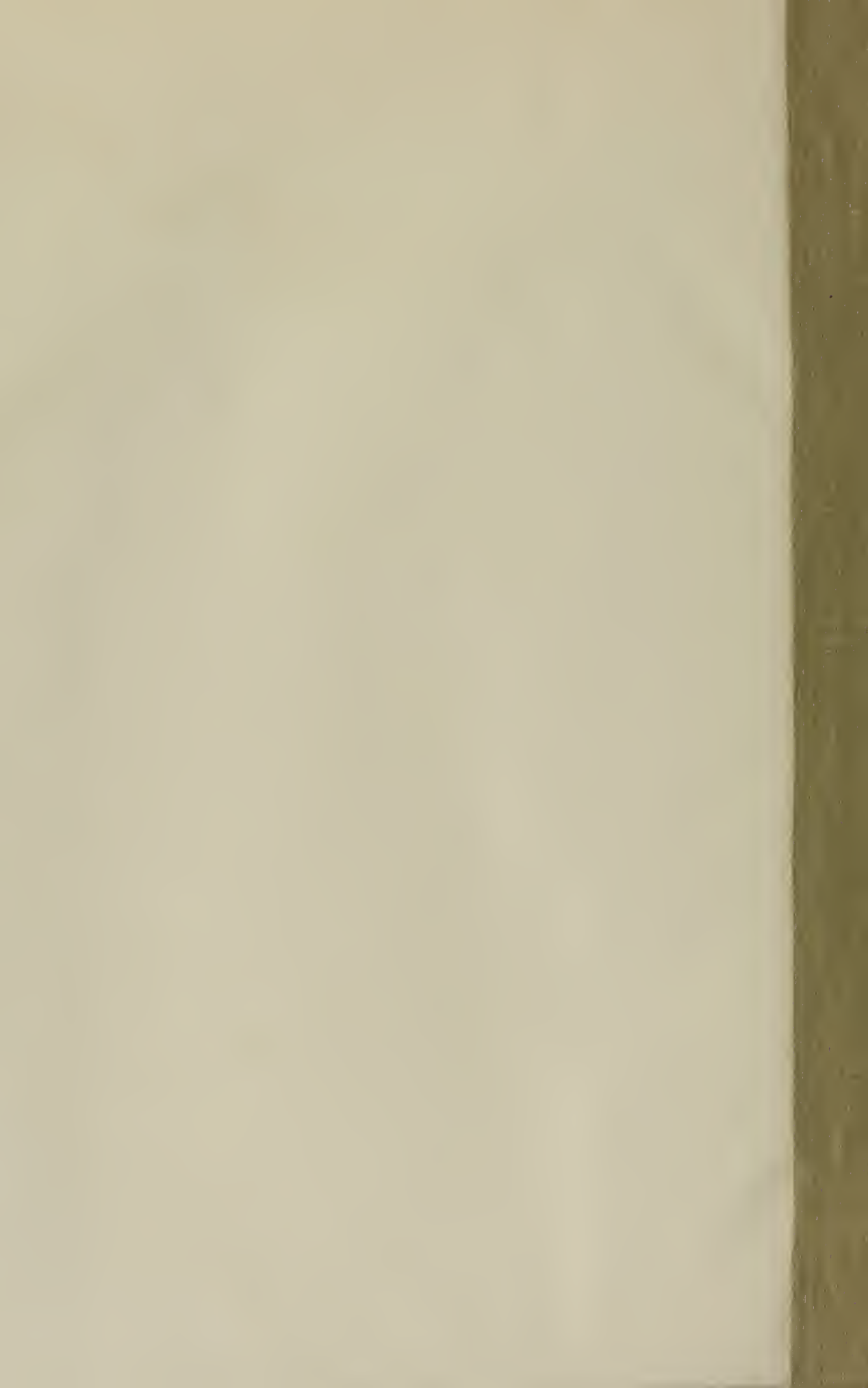
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ABSTRACT

The objective of this study was to examine the relationship between forward ship motion and the effects of aerodynamic and hydrodynamic disturbances on motions in the horizontal plane. It includes course control and stability analysis for the unsteered and steered cases (manual and automatic) using several sets of operating conditions.

Hydrodynamic and aerodynamic effects are considered to be functions of hull motion, rudder (steered cases), propeller and wind effects ratio. A dimensionless mathematical model has been developed and solved with respect to ship axes.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
low speed forward ship motion course control in the wind stability analysis for the automatically steered ship in the wind mathematical model in three degree of freedom						



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